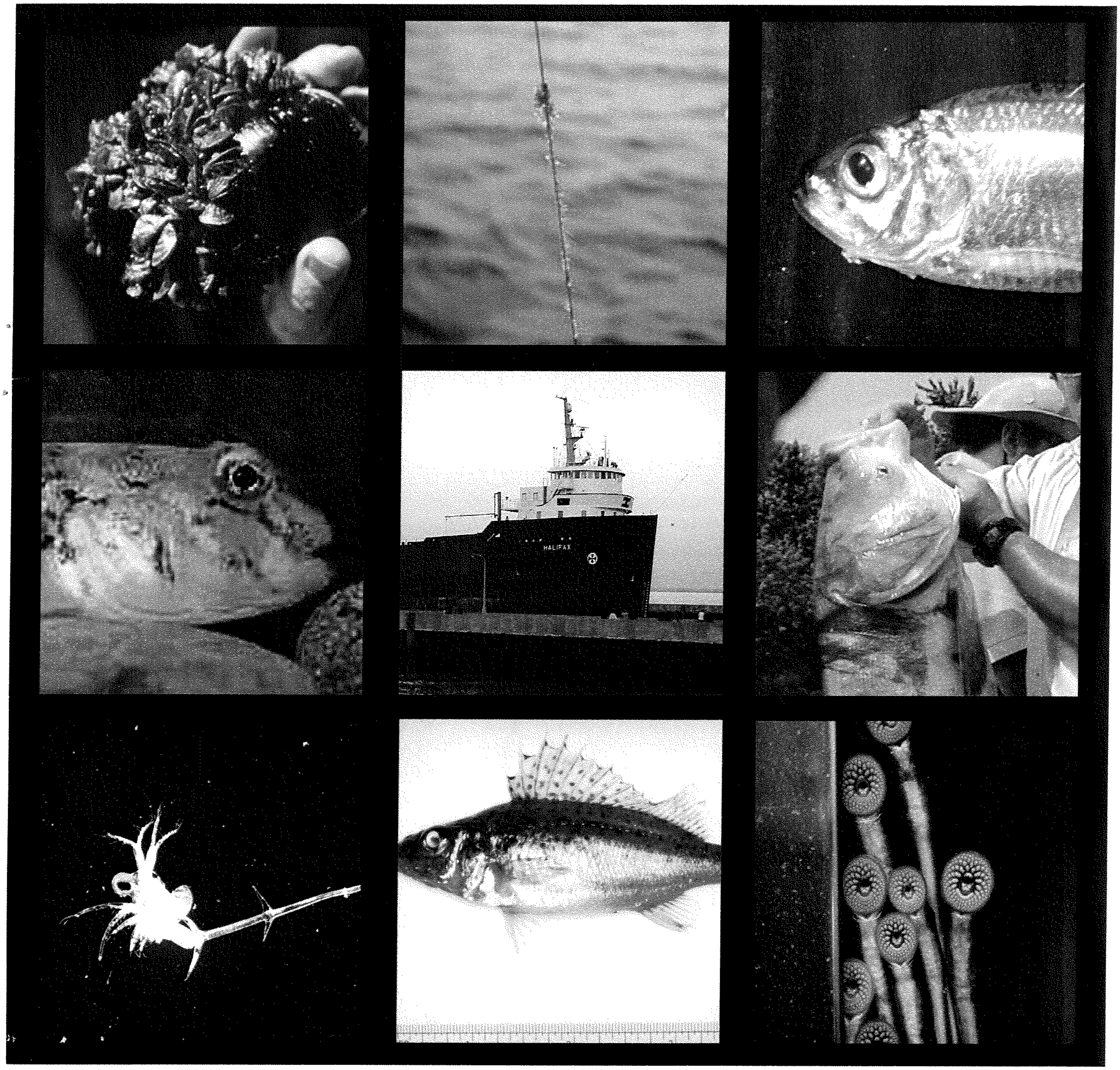

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October 2004

Ecosystem Shock:

The Devastating Impacts of Invasive Species on the Great Lakes Food Web

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By Gwen White, PhD., Michael Murray, PhD., and Sara E. Jackson

Acknowledgments

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One report in a series on Great Lakes Restoration

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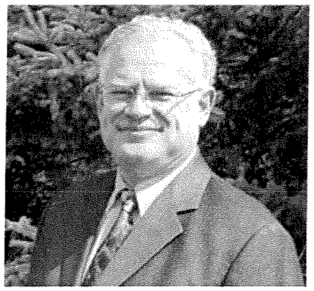
FOREWORD



One of the defining experiences of my life occurred on the shores of Lake Erie. I was young, and it was the first day of my family's summer vacation. I was excited to go fishing with my Dad. What promised to be a wonderful day, however, turned into a very painful one.

Standing on the waterfront, I looked out onto the lake and saw mats of dead fish floating in the water. I didn't know it at the time, but I was witnessing the actual extinction of a species – the blue pike of Lake Erie – and the near-death of the lake itself.

At that time, more than 30 years ago, chemical pollutants had poisoned Lake Erie. Wildlife perished. Scientists warned that the Great Lakes would die.

But they didn't.

That crisis led to the passage of the Clean Water Act, a ban on phosphate detergents, and a multi-billion dollar investment in wastewater treatment upgrades. Eventually the Great Lakes came back. Wildlife recovered. The rehabilitation of the Great Lakes became a conservation success story.

Now, however, the Great Lakes are again in a fight for their survival.

This time, the threat is not one of chemical pollutants (even though controlling chemical discharges remain an on-going priority). It is one of aquatic invasive species. Non-native organisms have entered the Great Lakes, out-competed native species for food and habitat and wreaked havoc on the ecosystem.

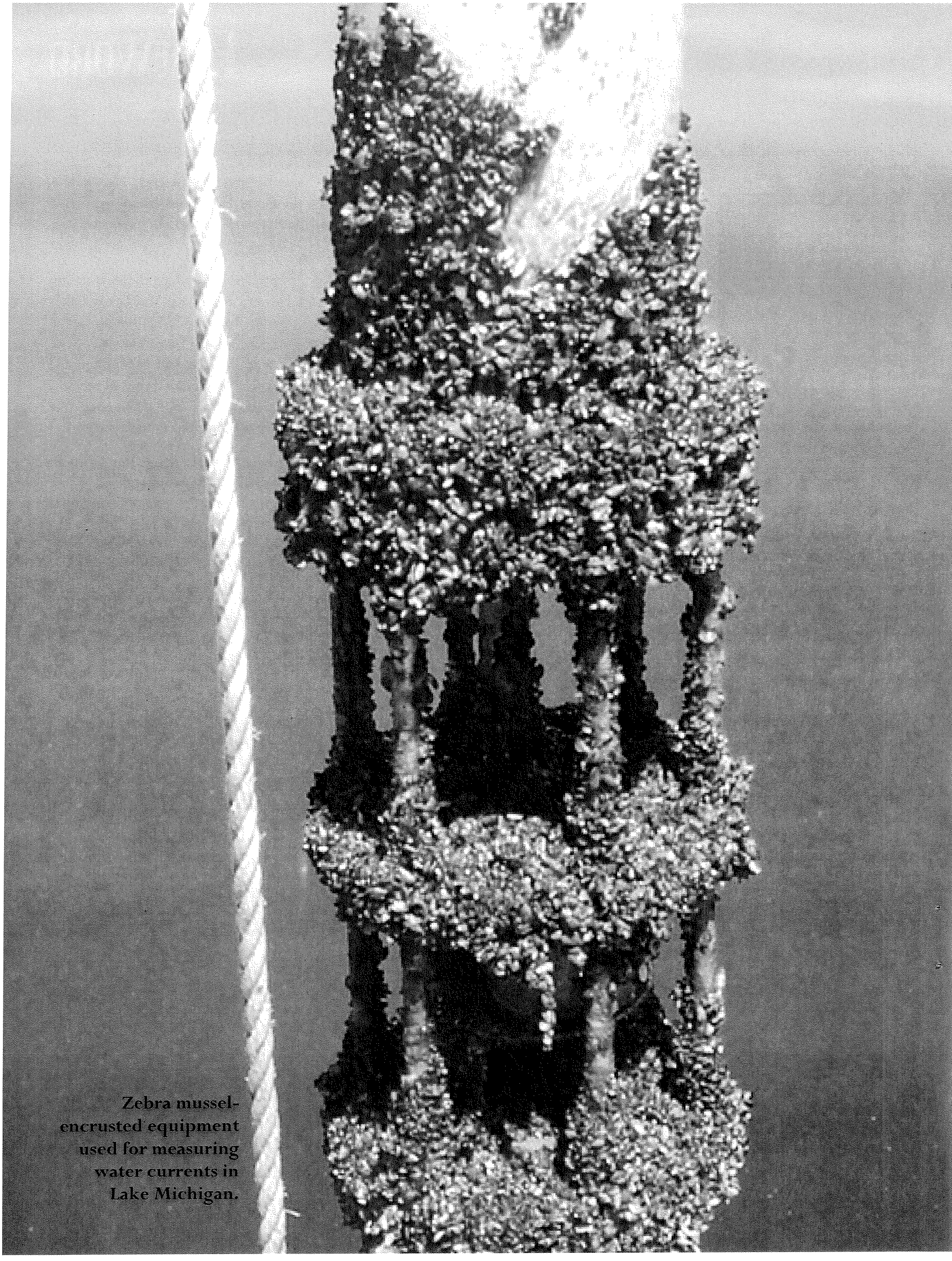
This report provides a comprehensive look at the devastating impacts that invasive species are having on the Great Lakes food web. Non-native species are harming fish at the top of the food web and decimating organisms at its base. The ecology of the lakes is profoundly changing before our eyes, and the repercussions can be felt by weekend anglers trying to reel in a decent catch and regional governments striving to meet the goals of the Great Lakes Water Quality Agreement.

The picture is grim. The prognosis is alarming. But solutions to this problem exist. And we still have time to act.

We hope that this report inspires legislators, scientists and industry leaders to work together to protect the Great Lakes and other U.S. waterways from the threat of invasive species.

For its part, the National Wildlife Federation is committed to shutting the door on invasive species. We are committed to protecting native wildlife and their aquatic habitat now so that they may be enjoyed now and for generations to come.

Larry Schweiger
President and CEO
National Wildlife Federation



Zebra mussel-encrusted equipment used for measuring water currents in Lake Michigan.

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Executive Summary

Sometimes referred to as the "Sweetwater Seas," the Great Lakes contain an incredible 20 percent of the world's surface freshwater. Their coastlines stretch over 10,000 miles, as long as the Atlantic and Pacific coastlines of the United States combined. Imagine pouring the Great Lakes out over the continental U.S. - they would fill the Grand Canyon and the rest of the nation would be submerged under 9 feet of water. The ecosystems supported by these lakes are equally vast - from varied shoreline to deepwater habitats. In monetary terms alone, the Great Lakes fisheries generate almost $7 billion each year through both commercial and recreational means. The Great Lakes are truly a national and global treasure.

Inflicting damage on a system this vast seems as if it would be difficult. Indeed it is. Over the past few centuries, though, human population expansion and development has inadvertently caused several ecosystem-wide shocks to the lakes. The harvesting of forests and establishment of agriculture in the region led to extensive erosion that damaged fish spawning habitat. Overfishing in the 19th century led to the extinction of several fish species such as the deepwater cicso. In the 20th century, chemical pollution destroyed some species and harmed others.

Once damaged, a water system this huge is very difficult to restore. Over time, we have managed to address and, at least, partially mend many of these earlier ecosystem-shocks. For example, Lake Erie, once declared nearly dead due to chemical pollution (in particular phosphorus), now is much cleaner. Though a number of problems with persistent toxic chemicals remain, pollution reductions have improved conditions for aquatic life and wildlife.

Now we are witnessing another wave of ecosystem shock. The entire food web – including the foundation of the vast Great Lakes ecosystem – is being disrupted by aquatic invasive species.

People who frequent the shores of the Great Lakes are becoming increasingly familiar with the side effects of some of these nuisance species invasions. They see the thousands of zebra mussel shells now covering the beaches. They stroll the shores and periodically notice hundreds of tiny invasive fish called alewives floating dead and rotting in the wave breaks. Curious about this sighting, they learn that groups of alewives tend to die off simultaneously causing potential human health hazards. Yet, these shoreline observations only hint at the full story.

Alewife, sea lamprey, round goby, Eurasian ruffe, spiny water flea, zebra mussel and quagga mussel are some of the more devastating species to be introduced to the Great Lakes system. All have had extreme adverse affects on significant native aquatic species, such as the commercially important lake trout and whitefish. Individually, scientists have studied these nuisance creatures and brainstormed ways to attempt to eradicate their populations. At best, we have only been successful in figuring out ways to manage their populations and reduce their negative impacts. Meanwhile, additional potentially devastating invasive species, such as Asian carp, are already on the doorstep to the Great Lakes, threatening to enter.

Perhaps one of the most alarming discoveries in the study of the relationship between native and invasive species in the Great Lakes is the depletion of a tiny freshwater shrimp called *Diporeia. Diporeia* historically has constituted up to 80 percent of the living material in offshore lakebed areas and is critically important as food for fish, particularly juvenile fish. In some locations in the lakes, this shrimp has gone from populations of over 10,000 organisms per square meter of lake bottom to zero in just a few years. Such a rapid and complete decline in a foundation species is unprecedented in the recorded history of the Great Lakes. Scientists do not know for sure the reason for this decline, but many believe that the zebra mussel population is the likely culprit. Thick colonies of zebra mussels, sometimes acres in area, cover large sections of the lakes' bottom and once established, interfere with the ability of *Diporeia* and some other organisms to thrive and reproduce.

As additional invaders enter the lakes and take hold, they place the entire Great Lakes fishery at an even higher risk of collapsing. And once such invasions occur, our options for recovery are quite limited. The lakes will not clean themselves of invasive species as they can, to a certain extent, chemical pollution once pollution sources are reduced or eliminated. Nor can we restore the food web simply by stocking high-profile species like trout and salmon or by limiting their harvest. We must develop and implement new management tools designed specifically to examine and protect the entire ecosystem — not just individual species. We must investigate and better understand food web dynamics and how they are being disrupted. And it is absolutely imperative that we stop new, even more damaging species from entering the Sweetwater Seas.

Congress is currently considering two highly effective opportunities for action. The first is legislation that would restrict activities (like ballast water discharges) that are the primary entrance routes for invasive species. This bill, called the National Aquatic Invasive Species Act (NAISA), could prevent new harmful species from invading the lakes. It would not, however, address the damage that is being done by the invasive species already present. Fortunately, another set of legislative proposals would finance a Great Lakes restoration initiative designed to restore habitat and species that have already been harmed. The Great Lakes restoration bills would provide billions of dollars for these and other restoration purposes. It will take a combination of these effective programs to ensure the survival of a healthy and diverse Great Lakes ecosystem.

1 ~ What's at Stake in the Great Lakes?

Zebra mussels on a Lake Erie beach.

The aquatic resources of the Great Lakes region contribute significantly to the economic development, culture, and recreation in the region, affecting eight states and two Canadian provinces. The Great Lakes and all of the connecting channels and rivers form the largest surface freshwater system in the world, containing nearly one-fifth of the world's supply of fresh surface water.[1] This abundant resource produces fish, attracts visitors to the region, and provides water for myriad additional uses of economic and recreational benefit. Sport fisheries support 75,000 jobs, while commercial fisheries provide an additional 9,000 jobs around the lakes.[2] Recreation and tourism in the region is valued at $15 billion annually with $6.89 billion annually related to the fishing industry.

The five lakes, though formed from the same processes of glaciation and following glacial retreat over the past 10,000 years, vary greatly in their physical settings and characteristics, from the relatively shallow and warmer Lake Erie (average depth of 62 feet) with its heavily developed shoreline in the south to the much larger, deeper and cooler Lake Superior (average depth of 483 feet) in the north. The land and climate around the lakes is also quite diverse, ranging from the colder climate, granite bedrock, and more heavily forested areas in the north to the warmer climate, more fertile soils, and intensive agriculture in the south. The forests and grasslands around the lakes have supported a diverse range of plants and animals, including moose, deer, foxes and wolves, while many waterways and wetlands have supported beaver and muskrat. As many as 180 species of fish were indigenous to the lakes themselves.[3]

Over the past two centuries, the Great Lakes region has seen dramatic change in human populations, land use, and resource management approaches. Between the 1820s and 1900s, the human population around the Great Lakes nearly tripled.[4] The building of settlements, increased use of the lakes for transportation, and the expansion of commercial fisheries all affected the lakes.[5] Logging during the latter decades of the 19th Century was extensive in parts of the region, and though the overall affect on Great Lakes water quality was unclear (apart from observations on sawdust pollution)[6], it is likely that soil erosion, changes in runoff and streamflow, and tributary habitat and water quality were affected.[7] With industrialization came the alteration of waterways through the building of dams, breakwaters, wharfs and dikes, construction and dredging of channels, and the filling of wetlands.[8] Though commercial fisheries had been in place for some time, overfishing became an issue with the collapse of the lake herring fishery in Lake Erie in the 1920s.[9] The combination of phosphates in detergents, excessive nutrients from agriculture, and poor waste management led to eutrophication (i.e., algal blooms and other symptoms of excessive nutrients) in parts of the lakes during the 1960s, and subsequently awareness increased of the problems of widespread contamination of the lakes by persistent toxic chemicals.[10] Other emerging threats to the lakes include changing lake levels and climate change.[11]

While some changes in recent decades – such as slower population and industrial growth rates and greater environmental awareness – have contributed to improved water quality in the lakes[12], Great Lakes fisheries remain at risk, in particular from the threats of invasive species.[13]

In the midst of these challenges, residents of the region recognize the value of the Great Lakes as a binational and global treasure. Polling conducted throughout the region in 2002 indicated that Great Lakes residents are highly committed to protecting and restoring what they consider to be a defining part of their homes and lives. Overall, 94% agreed (67% agree "strongly") that each of them has a personal responsibility to protect the Great Lakes. Nearly all — 96% — agree (78% "strongly") that we "need to do more to protect Great Lakes habitats from pollution".[14]

Today the Great Lakes are experiencing an ecosystem shock which appears to be due in large part to the introduction of aquatic invasive species that have established themselves in the Great Lakes, out-competed local species for food and habitat, and profoundly altered the food web of these five freshwater seas. The potential challenges to the Great Lakes ecosystem from these invasive species is likely to be greater and longer-lasting than any of the disruptions we have witnessed over the past two centuries.

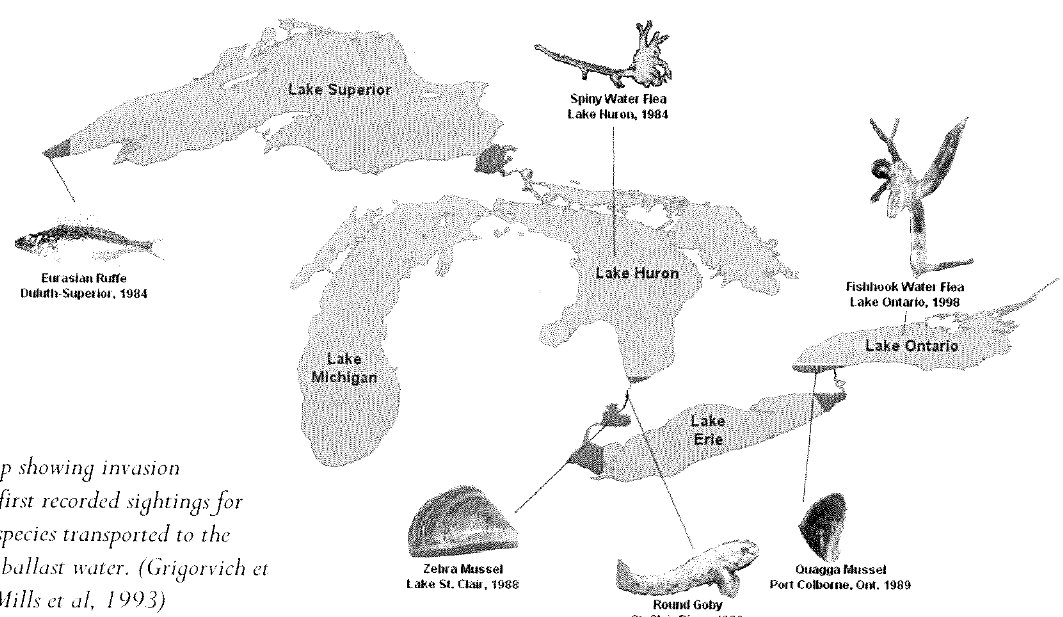
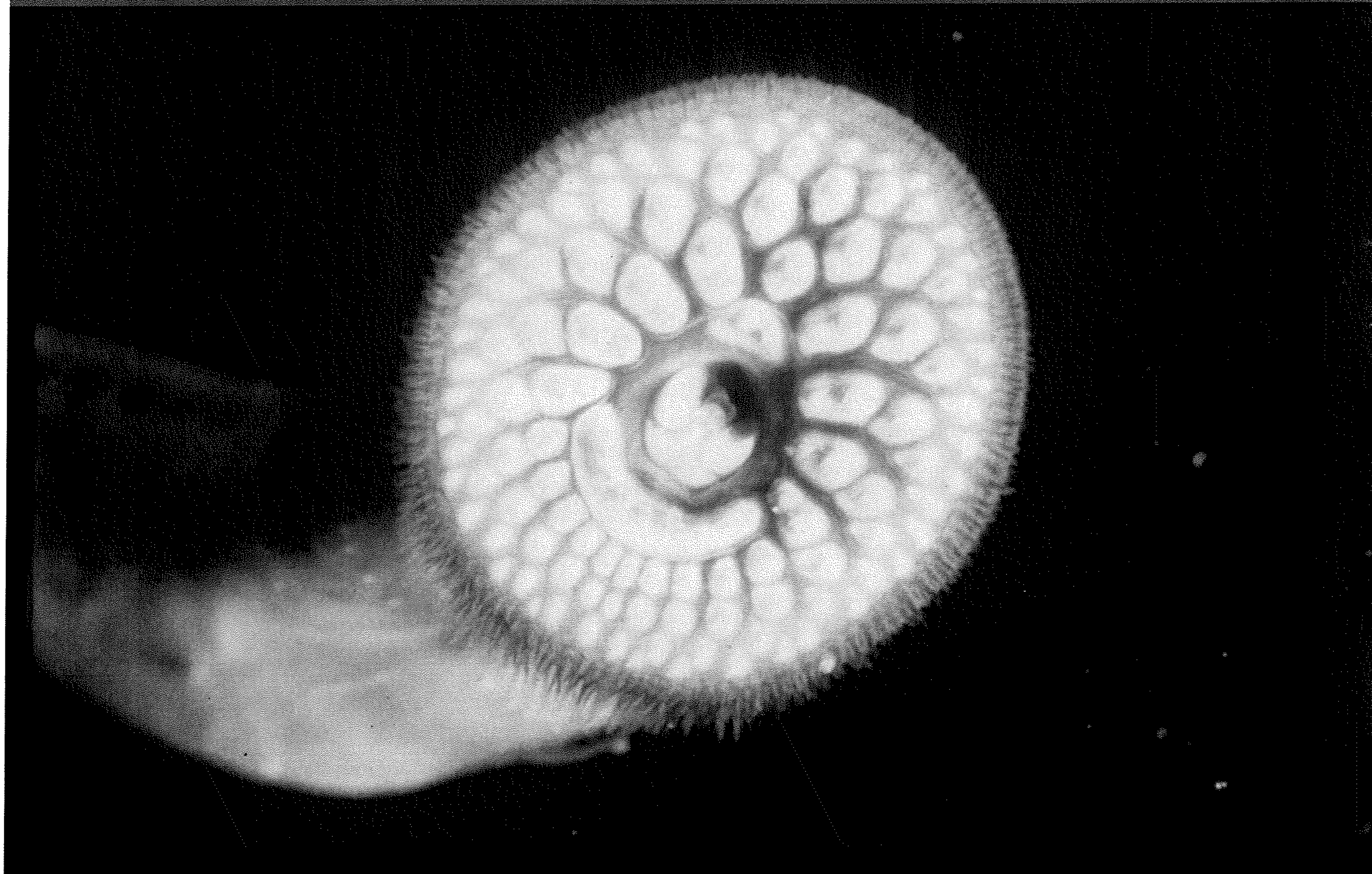


Figure 1: *Map showing invasion "hotspots" and first recorded sightings for select invasive species transported to the Great Lakes by ballast water. (Grigorvich et al, 2003 and Mills et al, 1993)*

2~ Invasive Species in the Great Lakes



Sea lamprey mouth

Over the past two centuries, more than 50,000 foreign plant and animal species have become established in the United States. About one in seven has become invasive, with damage and control costs estimated at more than $137 billion each year.[15] Nationally, about 42% — 400 of 958 — of the species that are listed as threatened or endangered under the Endangered Species Act are considered to be at risk primarily because of predation or competition with exotic species.[16] Indeed, invasive species comprise the second-largest threat to global biodiversity after habitat loss.

The Great Lakes region has been similarly affected by exotic species, and continues to be threatened by existing and potential new species invasions. Since the 1800s, the introduction of over 160 exotic species has irreversibly altered the region's ecosystem, causing dramatic changes in biological relationships and natural resource availability.[17] The effects of some introductions have been particularly acute – for example, sea lampreys played an important role in the collapse of lake trout fisheries in the upper Great Lakes in the 1940s-50s.[18] In addition to worries about the effects of invasive species on individual species, a wider concern is potential effects on the broader food web (see Box 1 for brief overview of Great Lakes food webs).

Introduced species enter the Great Lakes basin by multiple pathways. As of the early 1990s, the breakdown of the routes of introduction for 139 known aquatic invasive species was shipping (41 new species), unintentional releases (40), ship or barge canals, along railroads or highways, or deliberate releases (17), unknown entry vectors (14) and multiple entry mechanisms (27).[19] Unintentional releases can include unintentional fish stocking, aquarium release, and bait handling.[20]

About 70% of the 160 invasive species which have established themselves in the Great Lakes are native to the Ponto-Caspian region (a region of southeastern Europe and southwestern Asia that contains the Black, Azov, and Caspian Seas), with the second highest percentage originating from the Atlantic Coast of the United States.[21] An assessment of shipping patterns indicated that the Baltic and North Seas were the source regions for the majority of cargo-bearing ships — both number of ships and reported tonnage, for ships identified as no ballast on board, or NOBOB — entering the Great Lakes in 1997.[22]

The number of species invading from the Ponto-Caspian region surged beginning in the 1980s, primarily due to increased ship traffic, increased ship speed, and ballast water discharge. Factors such as extensive linkages of inland basins to the seas through canals and rivers, tolerance for wide-ranging salinities in many species, and transformations in the new environment that make habitat more suitable for additional exotic species coming from the same region all have contributed to increased numbers of invasions.[23]

Box I
Great Lakes Food Webs

The adjoining sketch shows a very simplified food web analogous to what might be found in one of the Great Lakes. From a biological standpoint, the lake can be divided into free, open (**"pelagic"**) waters and deeper (**"benthic"**) zones near and including the sediments. While many species tend to remain in one or another of the zones, other species (e.g. some fish and aquatic insects) sometimes move between them. An important aspect of the food web is the transfer of energy (in the form of nutrients) between organisms. In this case, **phytoplankton** — suspended microscopic plants (algae) or photosynthetic bacteria — grow by processing sunlight through photosynthesis. Phytoplankton can be consumed, either in the water or after they have died and fallen to the sediments, by either **zooplankton** (small suspended animals with limited powers of movement) or by **macroinvertebrates** (small animals lacking a backbone) in the sediments. These organisms can in turn be eaten either by other small animals, such as aquatic insects, or **forage fish**, such as smelt or alewife, which then can be eaten by **predator fish** such as lake trout or Pacific salmon. Changes to the food web can occur in several ways – including "top down" with the introduction of a new predator fish, or "bottom up" with the introduction of species that effect populations of either plankton or benthic organisms. In real lake systems, food webs are more complex, with many interacting components. However, the potential for food web disruption by invasive species or other phenomena always remains.

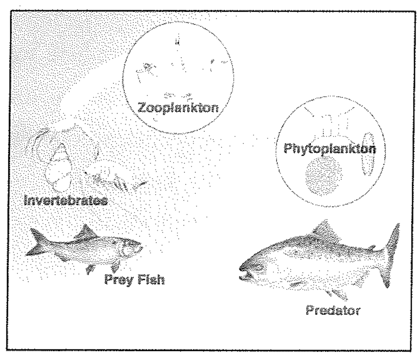


Figure 2: *Food web diagram (NOAA)*

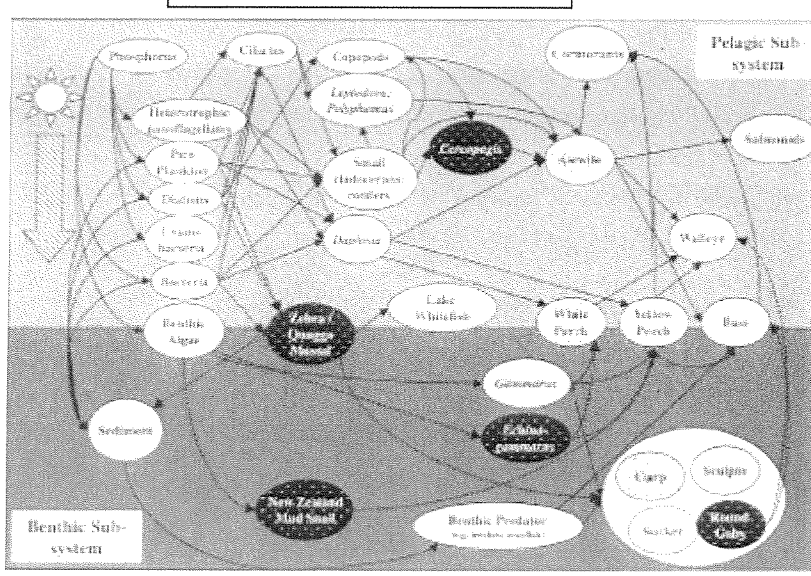


Figure 3: *Sample food web (Mills, et al., 2003)*

Box 2

Exotic Species Can Have Economic Value

Since recorded time began, people have brought plants and animals with them for food and other uses. Many introduced species of plants and animals, such as varieties of corn, wheat, rice, and other food crops, and cattle, poultry, and other livestock, now provide more than 98% of the U.S. food system at a value of approximately $800 billion per year.[24] Some predatory fish species (such as Pacific salmon) originally introduced in the Great Lakes to control invasive fish species have since become popular in the multi-billion-dollar recreational fishing industry. However, these types of introductions can still potentially have costs in terms of broader ecological changes not initially foreseen.

The Rate of Introduction is Increasing

As the use of the Great Lakes as a transportation route for commerce intensified, the rate of introduction of aquatic nuisance species also increased. Since the opening of the St. Lawrence Seaway in 1959, 77% of the new organisms established in the Great Lakes are attributed to ballast water discharge.[25]

Figure 4 shows the relationship between increased shipping activity and the increased rate of successful aquatic species invasions. Figure 5 indicates the increase in the cumulative number of invasive species in the Great Lakes. The rate of increase in recent decades is the highest observed thus far. Nearly 30% of invasive and introduced species in the Great Lakes became established after 1959.[26]

Who are the invaders?

We know of at least 160 exotic species that have invaded the Great Lakes since the 1800s; but in reality, there are probably many more that we have not yet discovered. The invaders we know about represent a wide variety and type of organisms. Based on data through the early 1990s, most of these species include aquatic or wetland plants (42%), invertebrates (20%) fishes (18%), and algae (17%).[27] Although it is difficult to conclusively identify the most damaging invaders because we do not yet know the full extent of the harm they are causing, three broad categories of organisms have already caused dramatic alterations to the ecosystem: fishes, mussels, and zooplankton.

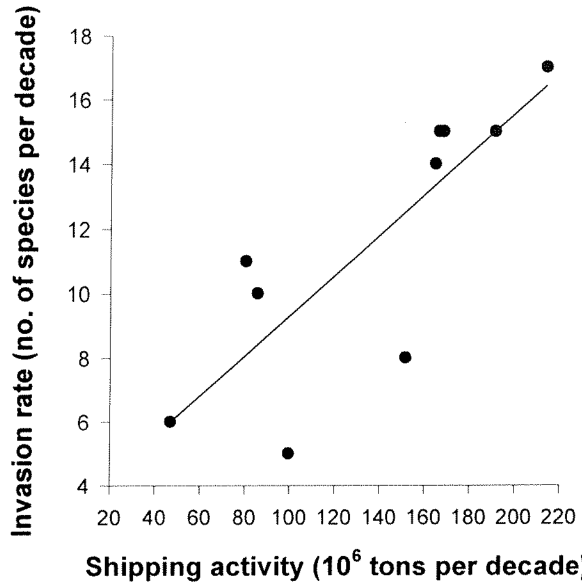


Figure 4: Increased shipping in the Great Lakes has led to an increased number of aquatic invasive species introductions – as shown by the relationship between the invasion rate and shipping activity in the Great Lakes (reproduced with permission from Ricciardi 2001)

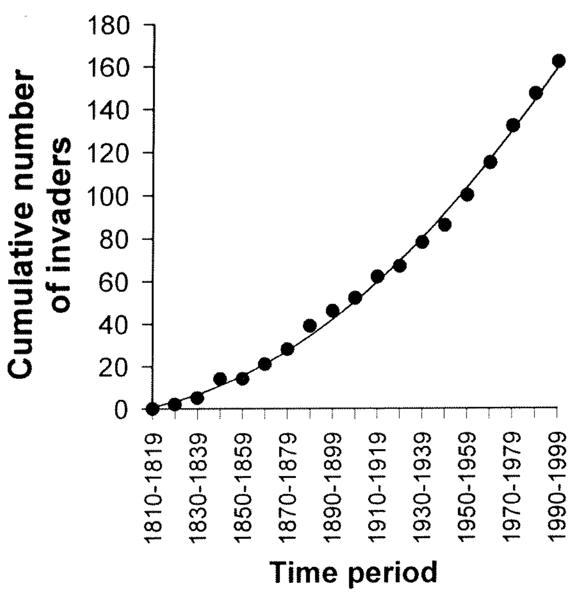
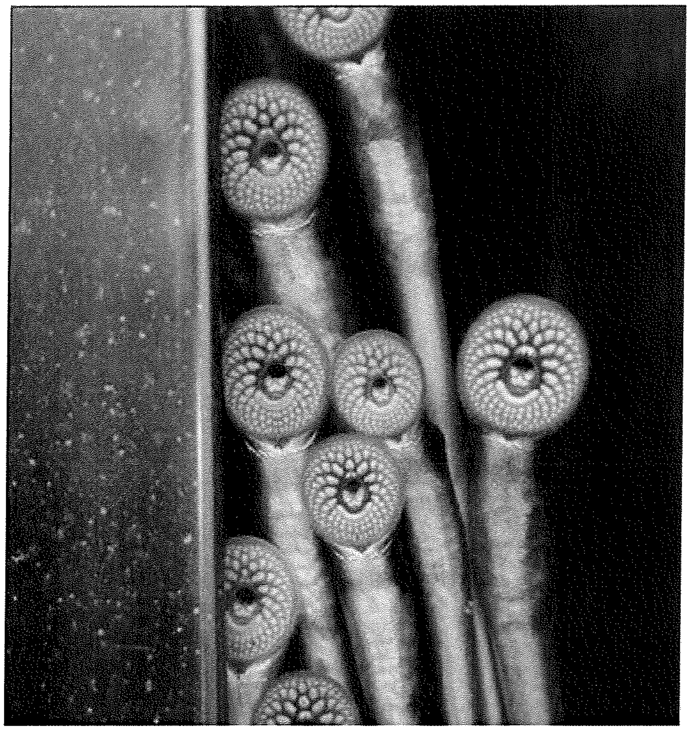


Figure 5: Cumulative number of nonindigenous invasive species established in the Great Lakes by decade (reproduced with permission from Ricciardi 2001).

Invading Nuisance Fish Degrade Native Fish Species

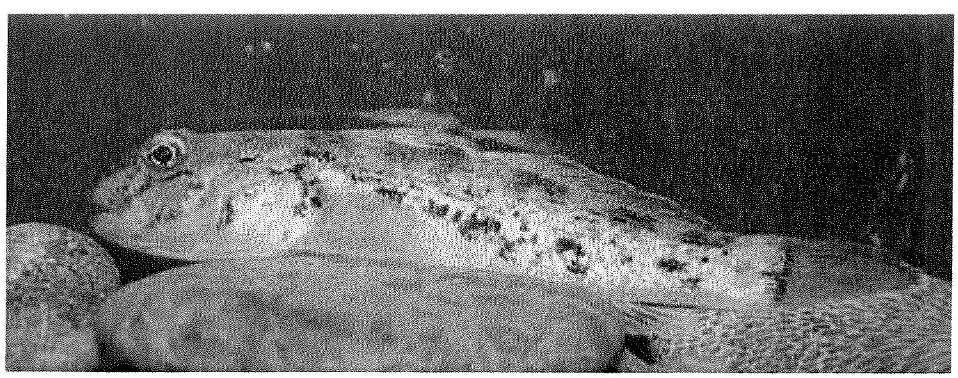
A number of invasive fish species have taken hold in the Great Lakes, either as a result of deliberate introductions or inadvertent invasions. Examples of species or groups of species that have had a significant effect on the fisheries and/or the broader food web are presented below.



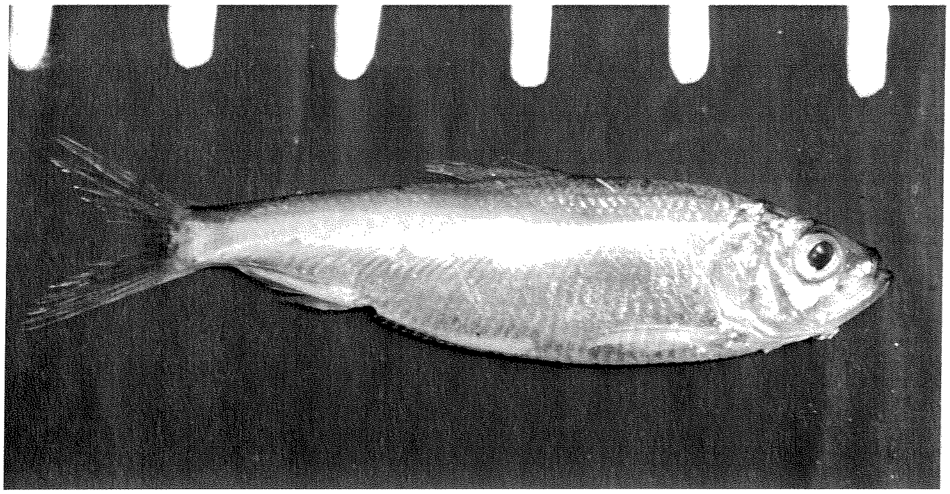
Sea lamprey

Sea Lamprey: The sea lamprey has most likely had the most significant impacts on Great Lakes fisheries of any invasive fish species. The lamprey was first identified in Lake Ontario in the 1830s, likely migrating west through the Erie Canal, although more recent genetic evidence indicates the species may be indigenous to Lake Ontario.[28] While the lampreys were not discovered in Lake Erie until 1921, they quickly spread to the upper three Great Lakes, reaching Lake Superior by 1938.[29] Lampreys affect the food web through habitat modification and, to a greater extent, through predation on fish.[30] The eel-like fish attaches to fish and drains them of blood and bodily fluids. An adult sea lamprey can kill up to 40 pounds of fish in 12-20 months. The combination of sea lamprey predation and overfishing led, to varying extents, to substantial declines or complete collapses of populations of lake trout, burbot, and lake whitefish in the middle of the 20th Century. Use of chemical control on sea lamprey larvae began in the late 1950s in Lake Superior and was extended to other lakes over the next three decades, and has eliminated spawning runs from a number of streams.[31] (See further discussion on populations of species affected by sea lamprey in Section 5).

Round Goby: Round gobies look and behave very similarly to the mottled sculpin, a fish native to the Great Lakes. However, these invaders are much more aggressive and out-compete the sculpins, as well as several other fish species, for food and habitat. First reported in the United States in the St. Clair River in 1990, they quickly spread, and now inhabit all five Great Lakes.[32] Once round gobies arrive in an area, a combination of aggressive behavior and prolific spawning allow the species to rapidly increase in abundance. They have been deemed responsible for local extirpation of mottled sculpins in Calumet Harbor, Lake Michigan, through competition for food sources, for space, and for spawning sites.[33] In addition, zebra mussels facilitate the introduction and establishment of round gobies by serving as a readily available food source for the non-native fish – round gobies are one of the few fish species that eat zebra mussels – and by creating habitat for small invertebrates that are the prey of small gobies.[34] The zebra mussel/round goby relationship thus represents a case of invasional meltdown, the process by which a group of nonindigenous species facilitates one another's invasion in various ways, increasing the likelihood of survival, the ecological impact, and possibly the magnitude of the impact.



Round goby



Alewife

ALEWIFE: Alewives are indigenous to lakes and streams in watersheds along the East Coast of the United States. As was the case with sea lamprey, alewives were abundant in Lake Ontario by the late 19th Century, likely having migrated from East Coast basins through the Erie Canal. The opening of the Welland Canal allowed for migration to the upper lakes, although it was only in 1931 that alewives were reported in Lake Erie. They were reported in Lake Huron in 1933, Lake Michigan in 1949, and Lake Superior in 1954[35], and had a significant affect on the fish community of most of the lakes. Alewives were held responsible for population declines in a number of fish species, including emerald shiner, bloater and yellow perch during the 1960s, and also likely were responsible for low abundances of deepwater sculpin in Lake Michigan by 1970. Alewives also likely contributed to reductions in burbot abundance in Lakes Huron, Michigan, and Ontario. In addition, alewives have continued to hinder the recovery of lake trout populations due to both their predation on lake trout young and reversely through early mortality syndrome (a thiamine deficiency in lake trout offspring caused by the parent's consumption of non-native species such as alewife as opposed to more nutritious native species).[36] A further problem with alewives is that they swim in dense schools and often die off in large numbers, littering beaches with rotting carcasses, and posing health threats. Ironically, some species introduced in the 1960s to control alewife populations (e.g. chinook salmon) are now popular sportfish, and are dependent on adequate alewife populations.[37]

EURASIAN RUFFE: The Eurasian ruffe was first found in the St. Louis River, Minn. in 1986, probably introduced via ballast water.[38] Ruffe can tolerate a wide spectrum of environmental and ecological conditions, ranging from shallow to deeper waters and low- to high-nutrient waters, although their abundance increases with the latter. The fish spawn on a variety of surfaces, and in some cases, more than once per year. Adults feed on macro invertebrates on lake sediments, and their primary predators are pikeperch and northern pike. Since their introduction, they have become the most abundant fish in the St. Louis River estuary – by the mid-1990s, their densities were over 4 times greater than the next most populous species (spottail shiner and troutperch).[39] While research has not indicated any substantial fish community changes in response to the ruffe invasion in the St. Louis River,[40] their tolerance for wide-ranging conditions, potential for widespread distribution, and their diverse diet of organisms on bottom sediments could eventually lead to pressures on other fish populations with similar diets.

Eurasian Ruffe

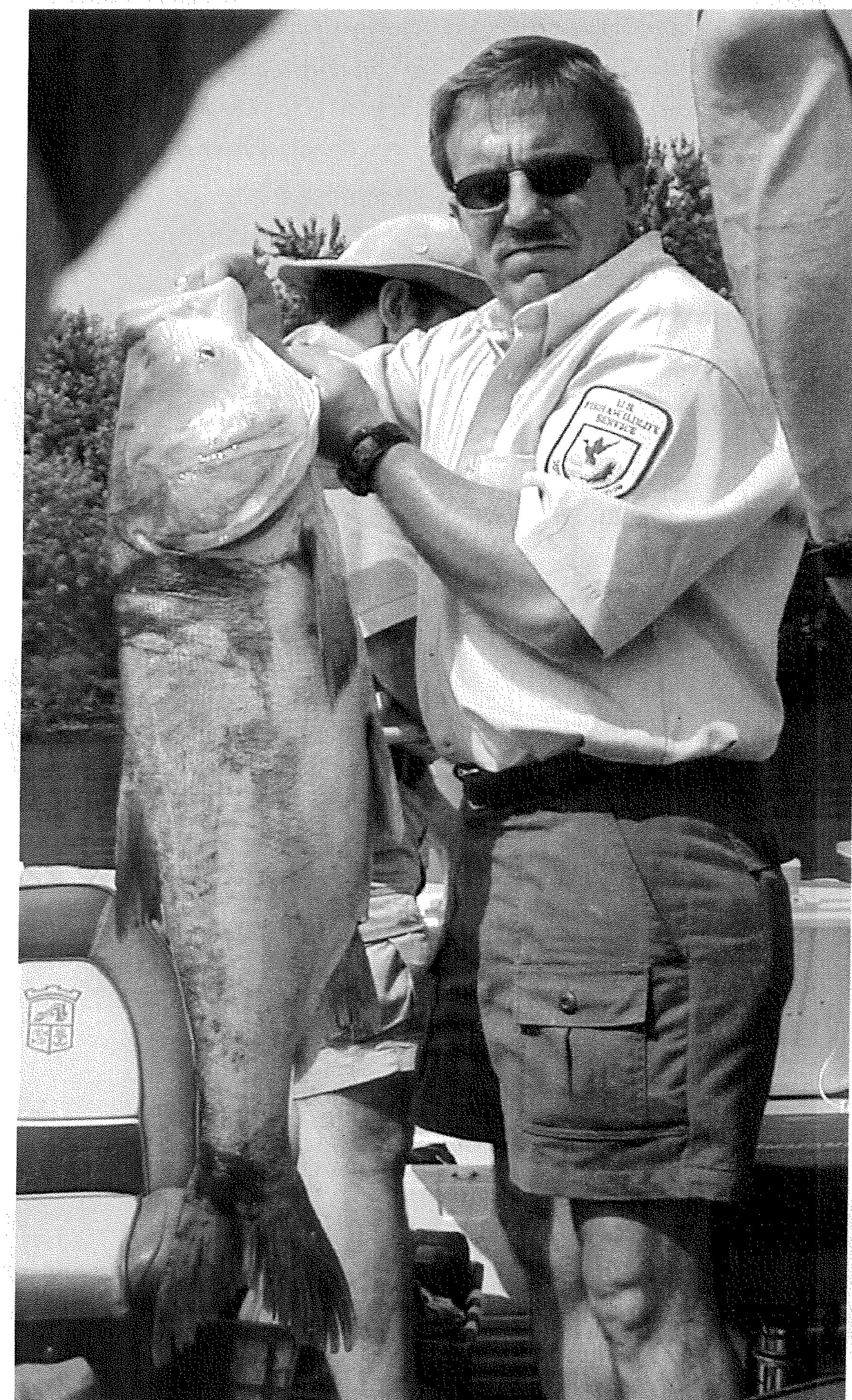
BOX 3

ASIAN CARP JUMPING TOWARDS THE GREAT LAKES

The closely-related bighead carp and silver carp (commonly referred to jointly as Asian carp) are a looming threat to the Great Lakes. Bighead carp are known to reach 90 pounds and silver carp 60 pounds. Because they are filter feeders that eat primarily plankton and they can attain such a large size, scientists suggest that these carp have the potential to deplete zooplankton populations. This can lead to reductions in populations of native species that rely on this food source, including all larval fishes, some adult fishes, and native mussels. Species of fish with high recreational and commercial value, including salmon and perch, are at risk from such competition in large rivers and the Great Lakes.

Asian carp likely escaped from catfish farms in the South during flooding in the 1990s or through accidental release. In less than 10 years they have spread up the Mississippi River system and have been collected in the Chicago Sanitary and Ship Canal only 25 miles away from entering Lake Michigan. In some of the big pools along the Mississippi River, Asian carp have multiplied so quickly that in less than a decade they make up 90 percent or more of the fish life. To stem the potential movement of fish between the Mississippi and Great Lakes waters, the Army Corps of Engineers has constructed an electrical barrier across the canal to repel fish in both directions. The barrier is not fail-safe and will require either backup generators or a second barrier for added security. A plan is currently in place to construct a second barrier.[41]

The silver carp have become infamous for their tendency to panic when they hear a boat motor, hurling themselves out of the water and into the path (or onto the deck) of passing vessels and personal watercraft. As dangerous as they may be to recreational boaters and anglers, they are even more perilous to the Great Lakes fishery. Despite some efforts by commercial anglers and state management agencies, no viable market for the large crop of carp has developed along the Mississippi River and its tributaries. If the Great Lakes are transformed into a "Great Carp Pond," there is no indication that a fishing industry would develop to replace losses to the current $6.89 billion industry.



Asian carp

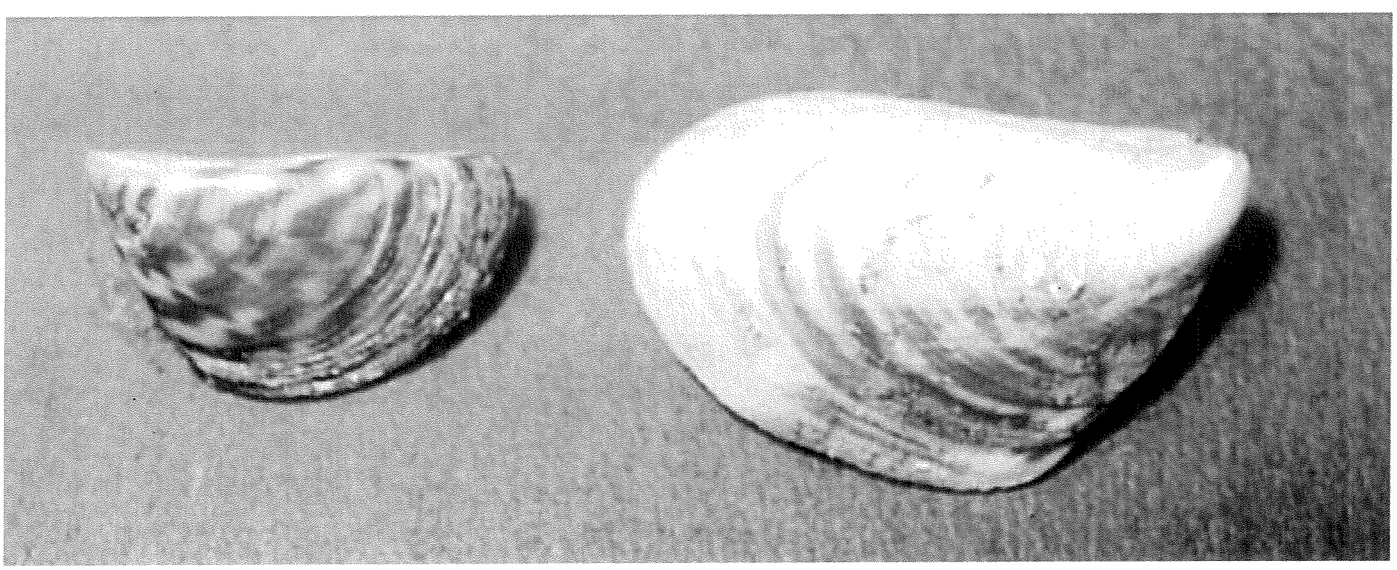
Exotic mussels re-make the bottom of the Great Lakes

Several invasive mussels have established themselves in the Great Lakes. The two most significant are the zebra and quagga mussels.

Zebra Mussel: The zebra mussel is a highly opportunistic mollusk that reproduces rapidly and consumes microscopic plants and animals from the water column in large quantities. Zebra mussels were first discovered in the Great Lakes in 1988 in Lake St. Clair, where they had been discharged in the ballast water from ocean-going vessels.[42] Because zebra mussels have a larval stage as plankton, they can easily be taken up in ballast water and passively distributed within a lake or downstream in rivers.[43] The adults can also attach to vessels and be transported to new water bodies as the boats enter them either directly or following overland transport. About the size of a fingernail, zebra mussels excrete a strong adhesive that allows them to attach to virtually anything, from rocks to municipal water intake pipes. The mussels can form thick colonies, acres in size, which cover the lakebed and occupy the habitat needed by native species. Even more damaging, zebra mussels are incredible filter-feeders, capable of consuming large quantities of microscopic aquatic plants and animals from the water column – and depriving native species of needed nutrients. Research indicates that zebra mussels remove suspended matter from the open water at a rate of up to 30 percent per day, and their filtering rate is over 10 times higher than that of native unionid mussels.[44] Such filtering fundamentally shifts the location of the food and energy in the Great Lakes, from the water column down into the sediments. While this shift has resulted in much clearer water in many parts of the Great Lakes, this clearer water means less nutrients for many fish species.

Scientists are just beginning to understand the impacts that zebra mussels are having on the Great Lakes. Researchers suspect that zebra mussels are a major factor in the collapse of a fundamental food source in the Great Lakes food web – the tiny, shrimp-like *Diporeia* (see Section 4). Scientists also believe the zebra mussel invasion has had negative impacts on a variety of fish species (see Section 5).

Quagga Mussel: A second mussel may be as damaging to the Great Lakes as the zebra mussel: the quagga mussel. Quagga mussels first appeared in the Great Lakes in 1989.[45] In size and appearance they are similar to zebra mussels, and like zebra mussels they colonize in thick mats over acres of lakebed. The major difference – and the one that alarms scientists – is that quagga mussels can colonize in deeper, colder water than zebra mussels. Zebra mussels thrive in the shallower and warmer lakebed areas along huge stretches of Lakes Michigan, Erie and Ontario, and Saginaw Bay. Now quagga mussels have begun to colonize additional lakebed areas, further decreasing the overall nutrients available to organisms important in the food web (see Section 4).[46]



A zebra mussel and quagga mussel

BOX 4

Zebra Mussels Contribute to Toxic Algae Blooms

An Example of an algae bloom

Researchers have found that zebra mussels can promote the growth of a toxic algae that is responsible for human and wildlife health concerns and the fouling of drinking water supplies. *Microcystis* is one of a class of algae that produce toxins (termed microcystins) that can cause harm and even death in fish, wildlife and people – for example, 55 people in Brazil died following exposure to microcystins. Blooms of this type of algae were common in parts of the lower Great Lakes before phosphorus reduction measures were taken in the 1970s. However, recent research indicates that zebra mussels may be contributing to a resurgence of the blooms in areas such as Saginaw Bay and Lake Erie. Zebra mussels consume and break down some algae, but selectively reject *Microcystis*, which can contribute to blooms of the toxic algae. In addition to the potentially harmful consequences on wildlife and people, the blooms can also effect the food web – the low intake rates and poor nutritional quality of *Microcystis* lead to decreased survival of zooplankton (microscopic animals) consuming the algae, which can then affect fish consuming the zooplankton.[47]

Unpalatable Zooplankton Thrive in the Water Column

Zooplankton are tiny animals that float in the water and feed on small, usually microscopic, floating plants called phytoplankton. Zooplankton are a significant source of food for many fish at some stage of their lifecycle – especially young fish. Because of their small size, easing their entry into ballast tanks, and the phenomenon of "resting stages," some zooplankton can easily become invaders into new ecosystems. As was the case with exotic mussels mentioned above, recent invasions by exotic zooplankton species have indicated the potential for nonindigenous species to disrupt the Great Lakes ecosystem.

One type of zooplankton of significant importance in

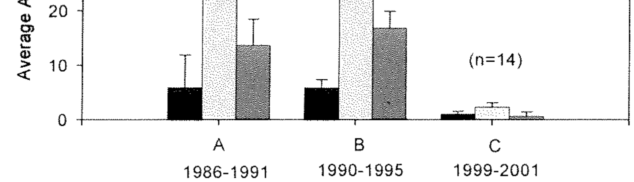
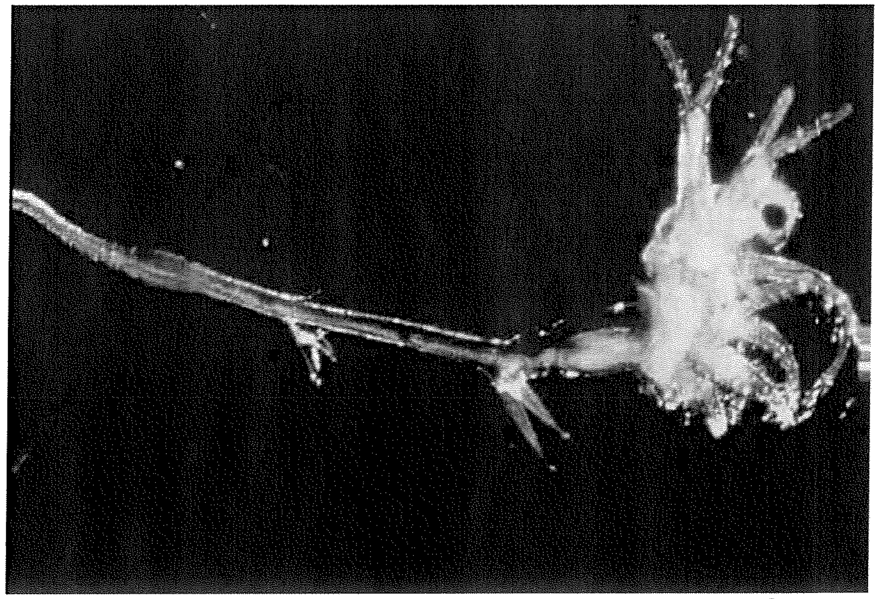


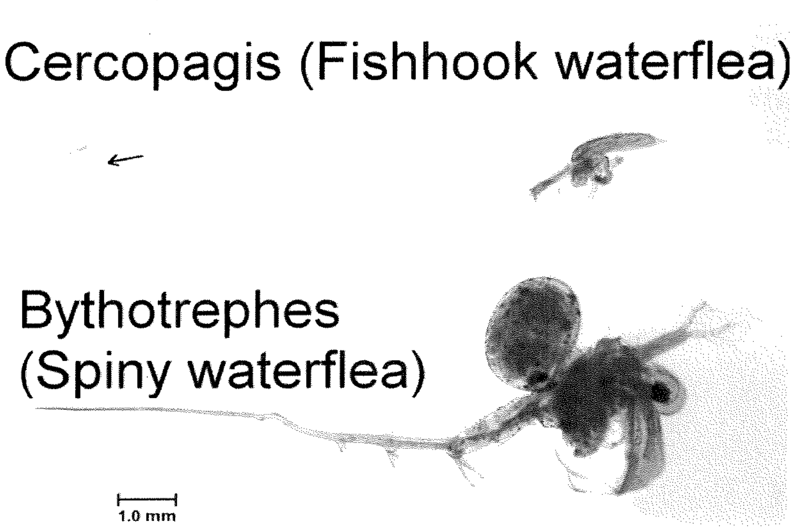
Figure 6: *Driven out: The introduction of the fishhook water flea in Lake Ontario in 1998 led to the dramatic reduction in three dominant zooplankton. (Reproduced with permission from Laxson, 2003.)*

freshwaters are cladocerans, also known as water fleas. Two recent zooplankton invaders of the Great Lakes come from this family – the spiny water flea and fishhook water flea. Both of these water fleas possess long sharply barbed tail spines that comprise upwards of 80% of the organisms' lengths. Many fish that otherwise eat zooplankton avoid both of these spiny creatures as prey and most of the smaller fish cannot effectively swallow them because of the long hooked tail spine. In addition, these larger zooplankton eat smaller zooplankton, competing directly with some fish for this important food source.



Spiny water flea

SPINY WATER FLEA: The spiny water flea native to northern Europe and Asia, was first found in the Great Lakes in Lake Ontario in 1982.[48] Over the next five years, this water flea was found throughout the Great Lakes and in some inland lakes in nearby states. Establishment of the spiny water flea in Lake Michigan was followed in 1987 by significant declines in abundance of three species of an important group of zooplankton, the Daphnia.[49] In a more recent study of smaller Canadian lakes, it was found that lakes invaded by the spiny water flea had significantly lower total amounts of the cladoceran zooplankton group, and on average 23 percent fewer of these species than the uninvaded lakes.[50]



Fishook waterflea and spiny waterflea

FISHHOOK WATER FLEA: The fishhook water flea is native to the Ponto-Caspian region (southeast Europe). It was first found in Lake Ontario in 1998 and quickly spread through lakes Ontario, Michigan, and Erie by 2001. The pattern this expansion took is consistent with the inter-lake transfer of ballast water; in addition, pleasure-craft are likely responsible for transfer from the Great Lakes to inland lakes.[51] Research on Lake Ontario indicated that the abundances of three dominant zooplankton declined dramatically after the introduction of fishhook water fleas in the lake (see Figure 6).[52]

GIANT CLADOCERAN: A third exotic zooplankton species, the giant cladoceran, is native to Africa, Asia, and Australia and most likely entered North America with African fish imported for the aquarium trade or to stock reservoirs.[53] Since 1995, it has been found in the Illinois River and a connecting channel to Lake Michigan through Chicago and now appears close to invading Lake Michigan; it was found in Lake Erie in 1999.[54] The giant cladoceran is much larger and has more numerous spines than similar native species making it difficult for young fish to eat; this could result in a reduction of food available in lakes, streams, and fish hatcheries where this zooplankter invades.

3: Cumulative Impacts of Many Invasive Species

Zebra mussels

Scientists estimate that about 10 percent of the aquatic species that have been introduced into the Great Lakes have caused significant ecological and economic damage.[55] While the impacts of some of these species are clear, the potential for other direct and indirect impacts remains to be determined. Scientists have, however, concluded that invasive species can affect multiple ecological levels. They influence various functional and behavioral factors for the native species, such as habitat use and foraging, abundance, distribution, food web relationships, and pathways for energy and nutrients.[56] They can alter the physical and chemical conditions of a habitat to an extent that the behavior, growth, and reproduction of native species are impaired. As the Great Lakes are invaded by increasing numbers of exotic species, scientists are discerning some disturbing patterns:

Profound alteration of the base of the food web. Over the past 15 years, invasions in the Great Lakes increasingly consist of tiny invertebrates. While they are important to their native food web, in the Great Lakes they are capable of accumulating in high densities and replacing native ecological equivalents. This dramatically reduces the amount of available nutrient for a number of native species in the system.[57] It also alters the way nutrients and contaminants travel through the food chain and ecosystems of the lakes.[58] (See discussion in next section).

Assault on the ecosystem on multiple fronts. A combination of multiple new species may make life even more difficult for native species, especially if these invaders are affecting the ecosystem at several different levels.[59] For example, in addition to taking up food energy that would otherwise be in species more readily consumed by forage fish, zebra mussel shells increase the complexity of the lakebed, making it difficult for fish to find food, and thus affecting the way nutrients and energy flow through the food web. The spiny water flea then affects the water column, out-competing native zooplankton. Then the introduced Eurasian ruffe may compete with native species for the limited food resources, further diminishing the survival of natives in the ecosystem.[60]

Facilitation of invasional meltdown (accelerating invasion). Some invaders may alter their new environment in ways that could make it easier for subsequent invasive species to establish themselves, thus accelerating the increase of new species over time.[61] Since 1970 there has been an average of one invader recorded every eight months in the Great Lakes, with the number of species established per decade increasing over time. None of these species have ever successfully been eliminated.[62]

Increased pressures on commercial and sportfish species. As invasive species consume energy, food, and habitat resources, these necessities become less available to the native species that are useful to humans. This may stress sport or commercially valuable species enough that harvest has to be reduced to sustain the population. For example, the Ohio Department of Natural Resources began

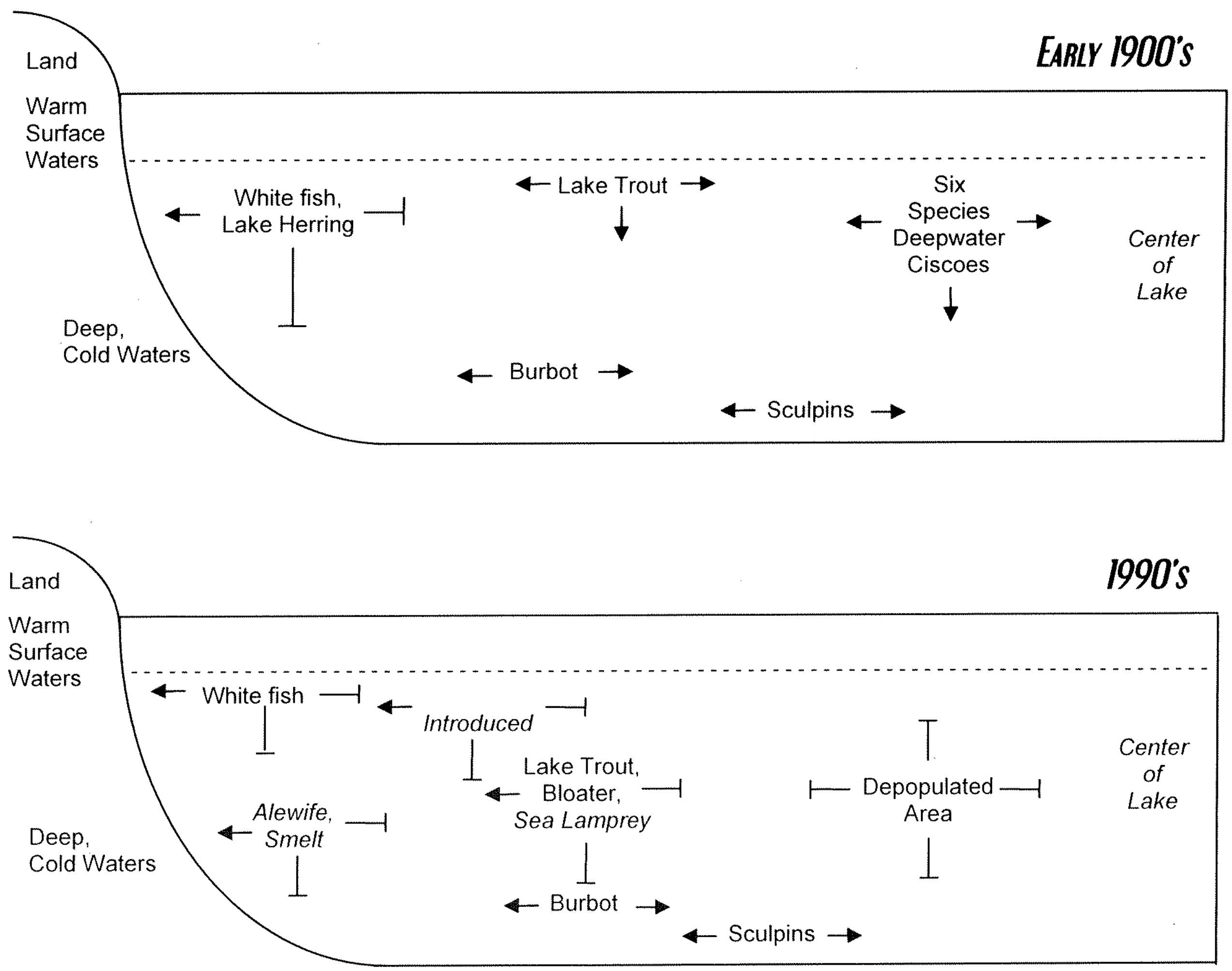
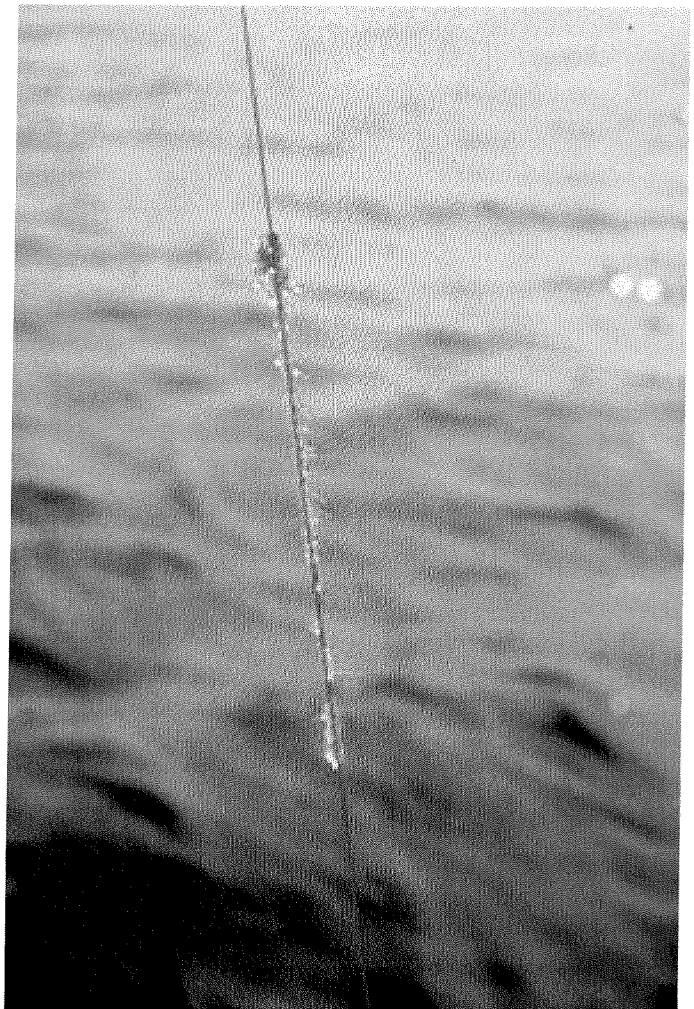


Figure 7: Changes in generalized distribution of offshore Great Lakes fishes from the early 1900s to the 1990s (adapted from Eshenroder and Burnham-Curtis, 1999).



Spiny water fleas coating a fishing line

to prohibit the catching of smallmouth bass in Lake Erie during May and June after a long-term study showed that round gobies decimated the nests by consuming eggs in the absence of the male bass guarding the nest.[63] Additional states are considering similar modification of bag limits for recreational anglers to balance the impacts of aquatic invasive species.

Changes in the broader species distribution of fishes. The combination of extinction and depletion of native fish species and introduction of non-native fish has significantly changed the fish distribution in the Great Lakes over the past century, as indicated in Figure 7. Among the changes:

- Among forage fish, lake herring and deepwater ciscoes have been replaced by smelt and alewife (with the most dramatic changes in Lake Ontario);
- Average lengths among the forage fish have decreased substantially (e.g. Lake Michigan deepwater cisco averaged from 203 to 333 mm (about 8 to 13 inches) in length in 1930, while alewife and smelt averaged 66 and 109 mm (about 2 ½ - 4 ¼ inches), respectively, in 1987);
- Invasive forage fish (smelt and alewives) inhabit much shallower waters than the native fish they have replaced, and bloaters whose numbers have recovered in Lakes Michigan and Huron tend to be in shallower waters than before;
- Introduced salmonids (predator fish such as coho and chinook salmon, and steelhead and brown trout), while within the size range of the historically dominant native fish (the lake trout), are shorter lived species, about five years for the introduced salmonids vs. over 20 years for lake trout;
- The introduction of salmonids has been producing a fish community dominated by piscivorous fish (fish that eat other fish) that inhabit the upper waters of the lakes vs. a community historically dominated by piscivorous fish that fed in deeper waters (lake trout and burbot).[64]

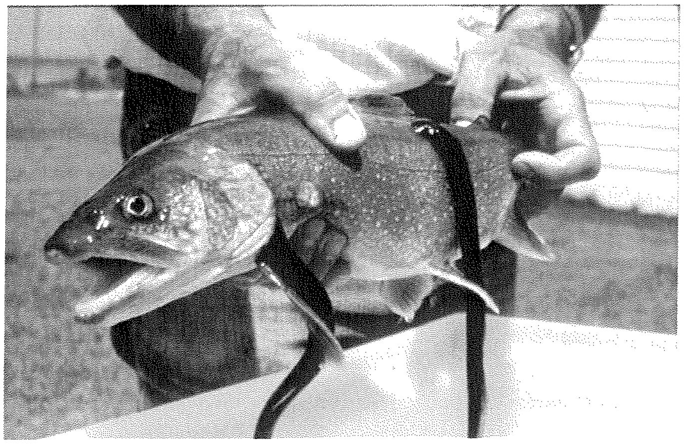
Section 5 includes more detailed discussions on impacts of invasive species on fish populations, as well as trends in commercial fish catches.

EXTENT OF GREAT LAKES FOOD WEB DISRUPTION

Foundation Species	Fish
Diporeia	Lake Trout
Fingernail clams	Yellow Perch
Zooplankton (3 species)	Whitefish
	Smallmouth Bass
	Lake Herring
	Deepwater Ciscoes
	Slimy Sculpin
	Mottled Sculpin

Impacts have varied significantly between species - from near extirpation throughout a lake (e.g. for lake trout) to local depletions (e.g. mottled sculpin).

Figure 8



Sea lamprey attached to a lake trout

Impacts on Infrastructure and Broader Economy Can Be Significant

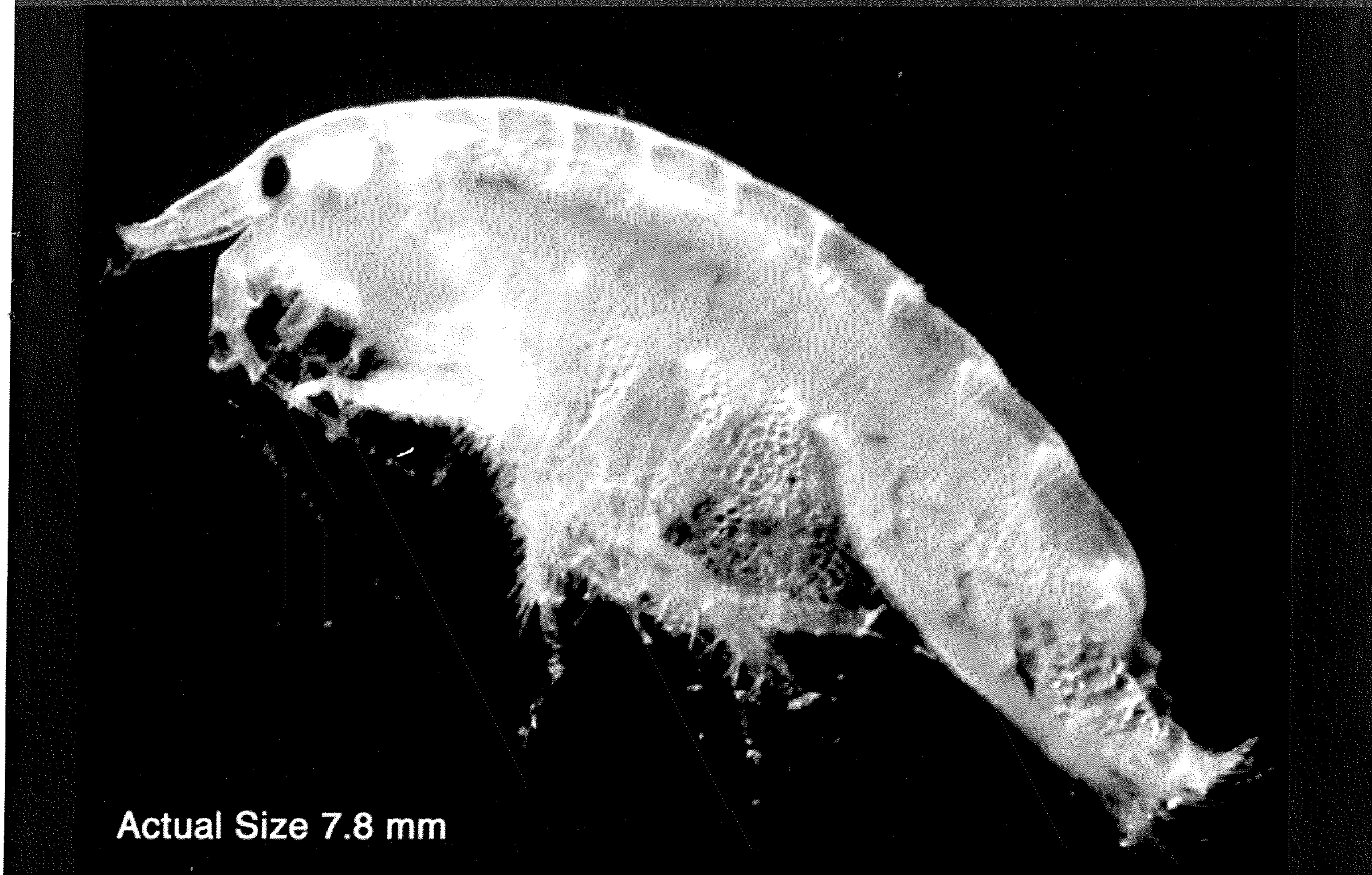
Invasive species introductions are a consequence of the economic welfare of our nation. Many species introductions, both intentional and unintentional, can be linked to economic activities, such as production, trade, and shipping.[65] The irony is that they are now impacting this economic prosperity.[66] Invasive species in general can affect the economy in a number of ways, including production, price and market effects, trade, food security and nutrition, human health and the environment, and financial costs.[67] Two ways that aquatic invasive species have affected infrastructure and the broader Great Lakes economy are indicated below:

Disrupting water infrastructure. Zebra mussels get inside water intake pipes and facilities, resulting in high costs to remove them. As they establish populations in more and more inland lakes in the Great Lakes basin (generally via private smallcraft transport), they put increasingly more water infrastructures at risk. In fact, University of Notre Dame researchers determined that it would be more cost-effective to spend $324,000 per year on efforts to prevent zebra mussel infestation on each inland lake associated with a power plant rather than pay the high costs of managing the negative impacts of zebra mussels on water withdrawals once populations were established in each lake.[68]

Imposing high unending control costs, if control is even feasible. The invasion of the sea lamprey had by the 1940s devastated populations of whitefish and lake trout and resulted in substantial economic losses to recreational and commercial fisheries.[69] From 1900 until trout population declines were caused by sea lamprey, the annual commercial harvests of lake trout exceeded 4.4, 6.3, and 5.5 million pounds annually for Lakes Superior, Michigan, and Huron respectively.[70] Control efforts were initiated in the 1950s, but by the early 1960s, the catch was only about 300,000 pounds. In 1992, annual sea lamprey control costs and research to reduce its predation were approximated at $10 million annually. Ongoing control efforts have resulted in a 90% reduction of sea lamprey populations in most areas, but now, resources spent on controlling these exotics are not available for other fisheries and resource management purposes. This earlier assessment found that the total value of the lost fishing opportunities plus indirect economic impacts in the Great Lakes could exceed $500 million annually.[71]

Lake trout with sea lamprey wounds

4: The Eroding Foundation of the Food Web



Diporeia

A healthy food web is a complex interrelationship in which each plant and animal benefits from and contributes to the success of the ecosystem. Typically the bottom of a food web begins with the tiniest creatures and their populations are endlessly bountiful. Moving up the food web, the animals become larger and their populations become fewer in number as they require more space and food. The top of the food web is very dependent on the health of all of the lower levels. When there is a disruption in the lower food web, negative effects ripple up through many populations and can be devastating.

A key part of the food web in the Great Lakes are macroinvertebrates (small animals without backbones) which link algae with fish communities. In particular in the deeper water of the lakes, four groups of organisms dominate the macroinvertebrate community — fingernail clams, certain worms (*Oligochaetes*), opossum shrimp (*Mysis*), and most significantly, a tiny shrimp-like amphipod called *Diporeia*. Together, these organisms constitute the vast majority of the deepwater food available to forage fish and other animals the Great Lakes, accounting for as much as 99% of the biomass available in the sediments.[72] Any changes to the sediment environment that affects these organisms therefore has the potential to greatly affect the fish and other predators reliant on this food source.

Diporeia

DIPOREIA

Diporeia, particularly compared to other invertebrates, are an especially important, high-energy food source for many fish.[73] In fact, most fish species feed on *Diporeia* at some stage of their life cycle.[74] In deeper water habitats, *Diporeia* consume nearly one-quarter (23%) of the total annual production of phytoplankton[75] and, in Lake Michigan, they consume over 60% of the spring diatom bloom (blooms of an algae rich in lipids, another nutrient),[76] making these nutrients available to move up the food web.

Yet *Diporeia*, a key component of the Great Lakes food web, has dramatically declined over the past 20 years – in some cases decreasing from over 10,000 organisms per square meter to virtually zero. The scale and short time frame of the declines are particularly disturbing; fish species reliant on *Diporeia* need to find other equally nutritious food sources in order to survive in areas where the amphipod is in steep decline. If some of those food sources are less easily digested or available, the species would not likely be able to evolve characteristics quickly enough to compensate (see discussion in Section 5 on impacts of *Diporeia* declines).

BOX 5

LOCKING UP PRODUCTION IN THE LAKEBED: EXPANSION OF MAT-FORMING BACTERIA

At the same time that *Diporeia* disappeared in Lake Ontario, a bacterium called *Thioploca* began to form in unusually extensive mats and soon became the most dominant organism in the sediments of the upper lakebed. More energy began being used in the development of bacterial mats, leaving fish and other resources useful to humans deprived of nutrients.[77] While some exotic species such as alewife can be viable food sources for commercial and sport fish species, bacterial mats do not provide food or habitat for these species. As the mats developed, the lakebed community was reduced to a few species of worms and a few tiny clam species. Additionally, nitrate has doubled in Lake Ontario over the past several decades,[78] which may also support the spread of the bacterial mats. Prior to 1991, dense *Diporeia* populations (up to 16,000 individuals per square meter[79]) probably directly and indirectly — by keeping the lakebed more oxygenated — reduced the development of the bacterial mats on the lakebed.[80]

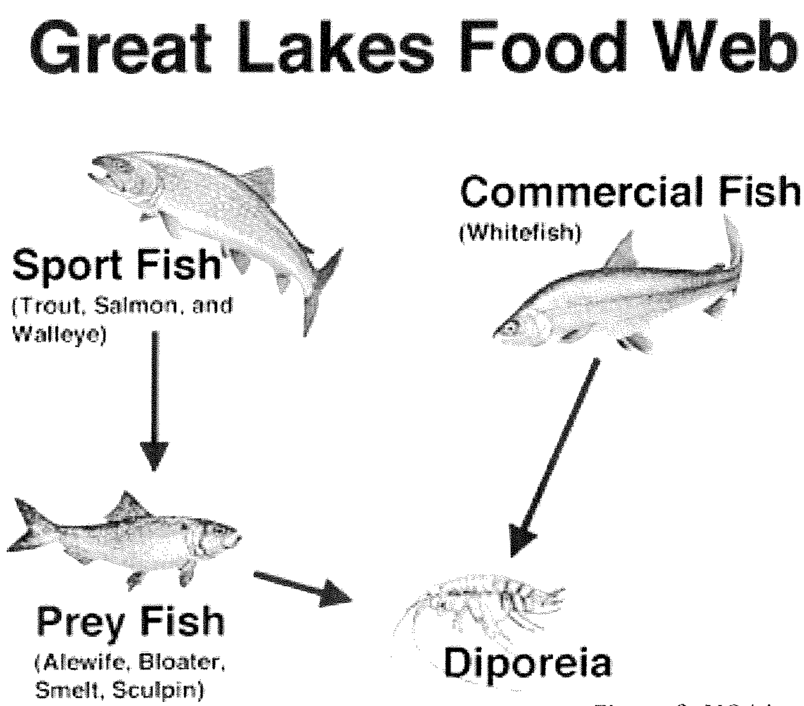
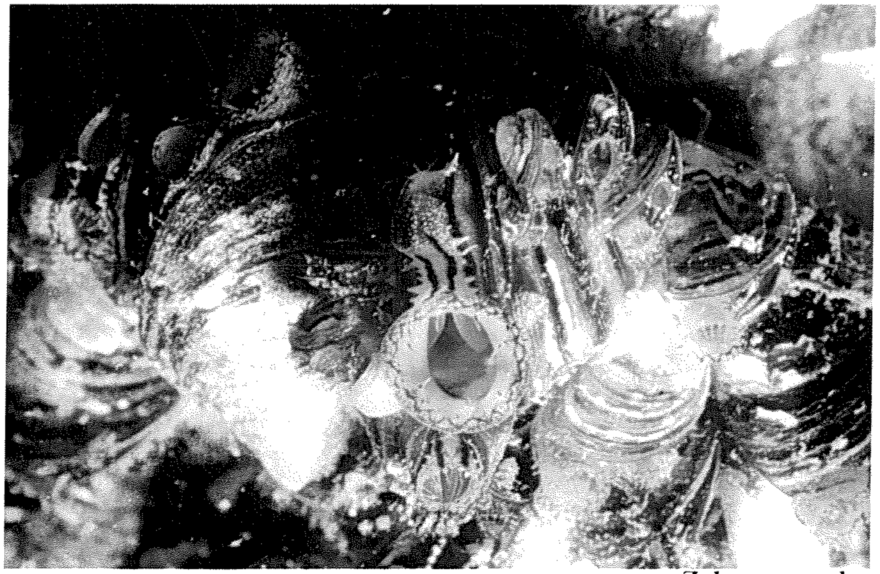


Figure 9: NOAA



Zebra mussels

As *Diporeia* disappears, the pressure will be greater on a less abundant food source, the opossum shrimp. If the opossum shrimp is susceptible to the same factors that are causing the degradation in *Diporeia,* few other alternatives are left to support many fish and other aquatic animals in deeper waters of the Great Lakes. Indeed, scientists have observed impacts on fish that depend on *Diporeia* as a food source:

- In Lake Erie, smelt stocks have declined since the loss of *Diporeia*;
- In Lake Ontario, slimy sculpin and young lake trout, species that also rely on *Diporeia*, have declined;
- In Lake Michigan, whitefish have shifted from eating *Diporeia* to the more abundant, but less nutritious zebra mussel, leading to leaner, smaller whitefish.[87]

Disappearance of High Quality Food Coincides with the Appearance of Exotic Mussels

Since their discovery in the Great Lakes, zebra and quagga mussels have colonized a wide variety of underwater surfaces to depths of 130 meters[81] and have reached densities of up to 340,000 per square meter in some areas.[82] Zebra and quagga mussels are aggressive and efficient filter-feeders that consume large volumes of nutrients, dramatically decreasing suspended nutrients that are critical to other species.[83] In particular, this diversion of food resources may deprive *Diporeia* and other deeper water macroinvertebrates of food settling from the above water.[84]

Substantial declines in *Diporeia* populations, as well as that of fingernail clams, have been observed in several of the Great Lakes since the establishment of zebra mussels. Although the connection between zebra mussel invasion and significant *Diporeia* declines coincides in time, direct causal links have not been clearly established. Although other potential explanations for the declines have been proposed – including decreasing algal nutrient resources and indirect competition with zebra mussel colonies in shallow water – these alone cannot explain the total elimination of *Diporeia* from favorable habitats.[85] Other factors that may affect *Diporeia* include disease from pathogens[86] — though none have been reported in the literature, as well as additional factors — yet unknown.

Fingernail Clams: As devastating as the disappearance of *Diporeia* may be for the Great Lakes fishery, it may be only part of a broader decline near the bottom of the food web. Scientists have also discovered what looks like a parallel depletion in another species, the fingernail clams. These clams are found in the upper sections of sediments and feed on microorganisms in the water between sediment particles. Because some fingernail clams filter-feed directly on algae, zebra mussels can be in direct competition with them for food. Research in Lake Michigan revealed substantial declines in fingernail clams through the mid-1980s and into

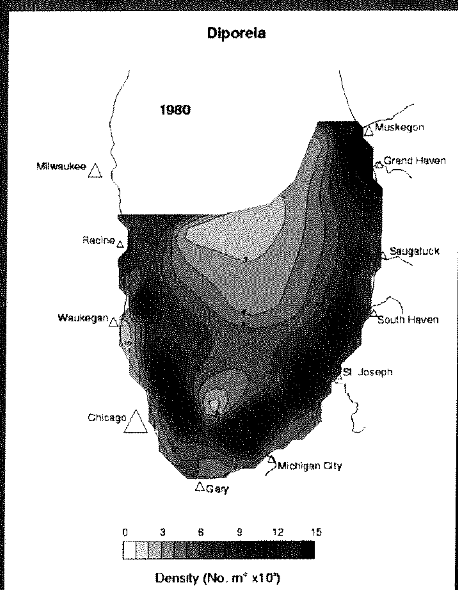
Fingernail clam

Diporeia in Lake Michigan: Examples of Declines in these Lakebed Food Resources

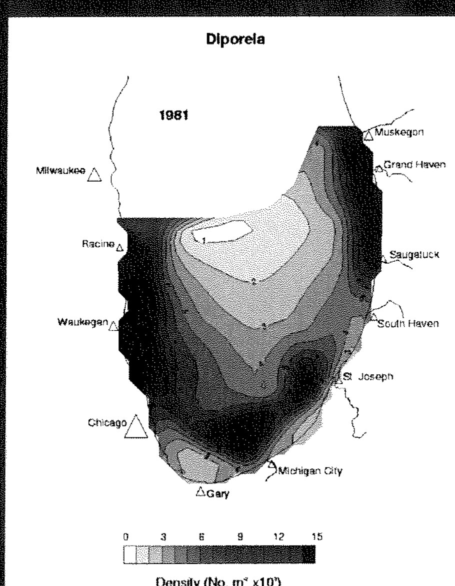
Diporeia numbers in southern Lake Michigan dropped slightly during the 1980s, but decreased much more rapidly beginning in the early 1990s following the introduction of zebra mussels to the lake in 1989.[88]

- The density of *Diporeia* at the Grand Haven, MI station dropped from 10,000 per square meter in the 1980s and early 1990s to 110 per square meter in 1999 after zebra mussels were discovered in the area in 1992 – a 99 percent decline.[89]
- The mean density of *Diporeia* off Muskegon, MI declined from 5,569 per square meter to 1,422 per square meter.
- By 1998, *Diporeia* declined in southern Lake Michigan and were rare or absent off Grand Haven, Saugatuck, South Haven, and St. Joseph out to depths of 70 meters.[90]

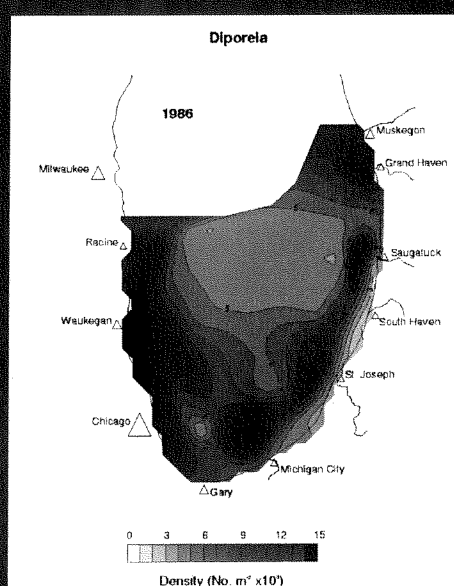
Figure 10: Changes in abundance of Diporeia in sediments of southern Lake Michigan from 1980-2000. By 1998, large sections of nearshore waters in the southern and southeastern portion of the lake were supporting few if any numbers of the shrimp-like organism. (Graphic from T. Nalepa, Great Lakes Environmental Research Laboratory, NOAA)



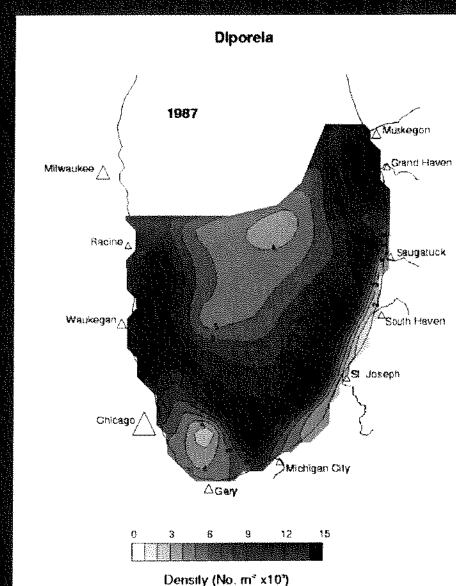
1980



1981



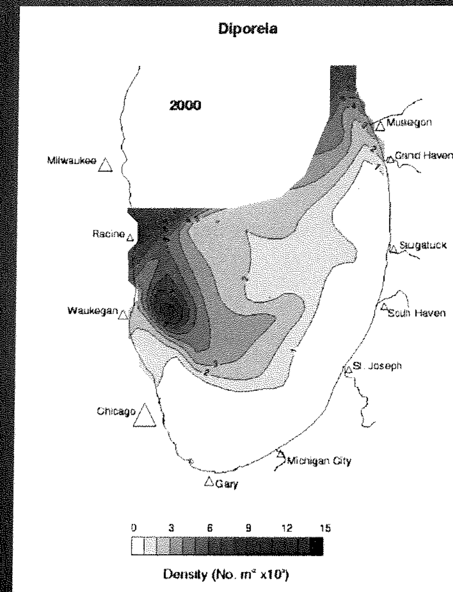
1986



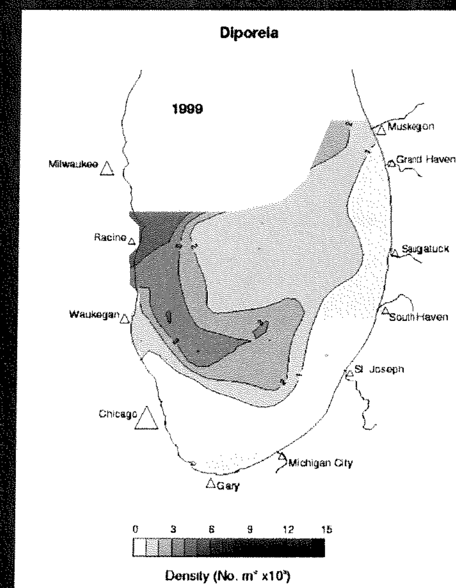
1987

Similar changes in *Diporeia* populations have been observed in sampling of a number of sites in Lake Ontario:

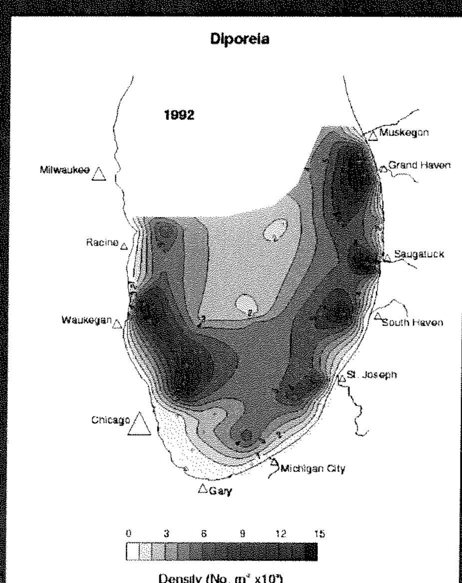
- Mean densities of *Diporeia* were at least 130 times greater in 1964 and 1972 than in 1997 after zebra mussel establishment.
- At locations where *Diporeia* was abundant, densities dropped to 15% of their former levels in three years (averaged 6,363 per square meter in 1994 and only 954 per square meter in 1997).
- The percentage of stations where no or very few *Diporeia* were found more than doubled from 40% in 1994 to 84% in 1997.
- A zone of very low *Diporeia* density (less than 4 individuals per square meter) extends as far as 16 miles (26 kilometers) off-shore and to depths of 656 feet (200 meters) over 40% of the total surface area of Lake Ontario soft sediments in 1997.



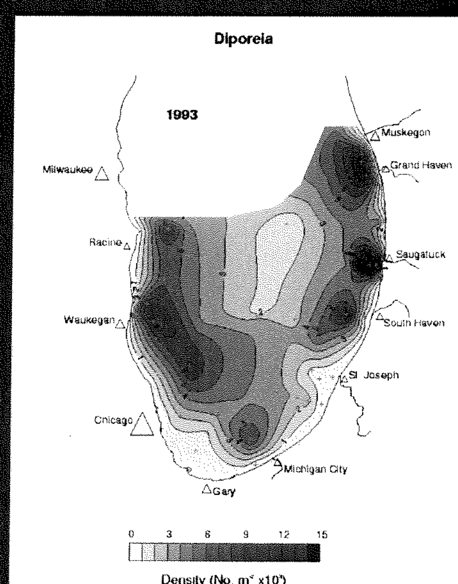
2000



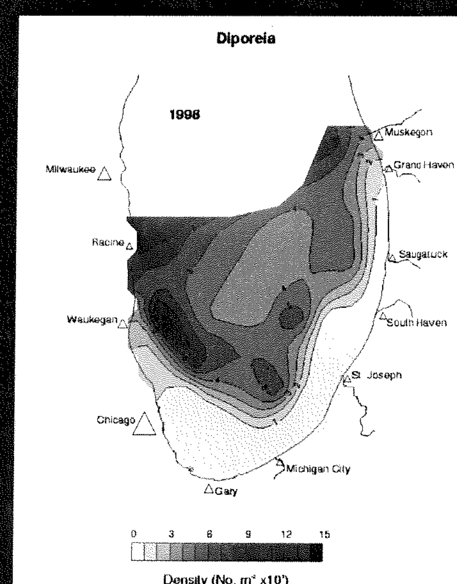
1999



1992



1993



1998

the early 1990s; yet the widespread nature of the declines – including beyond areas of zebra mussel infestation – suggested that zebra mussels may have had a more minor role, with nutrient reductions and declining primary productivity playing a larger role.[91]

However, in another study near Michigan City, Indiana, growth of zebra mussels on fingernail clams was observed, and the researchers hypothesized that zebra mussel colonization caused the significant declines in fingernail clams seen from 1992-1997, from a median of 832 to13 clams per square meter.[92] Similar results have been found in Lake Erie, where the clams declined significantly in areas where zebra mussels were abundant.[93] In western Lake Ontario, a significant increase in the population of zebra mussels was accompanied by a complete crash of two species of fingernail clams.[94] (See Figure 11).

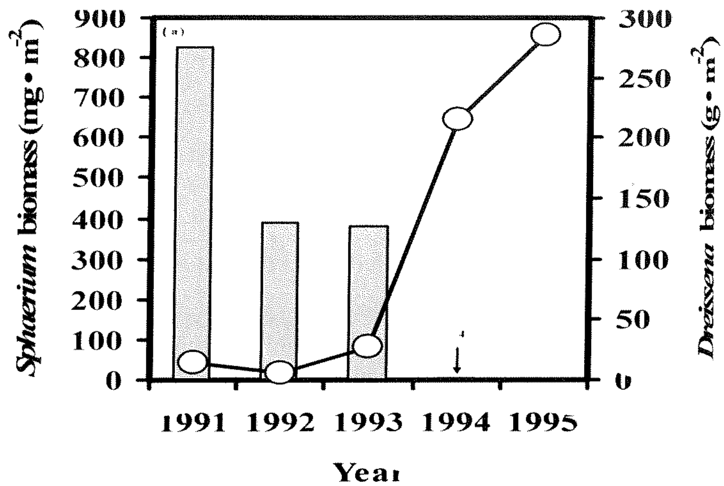


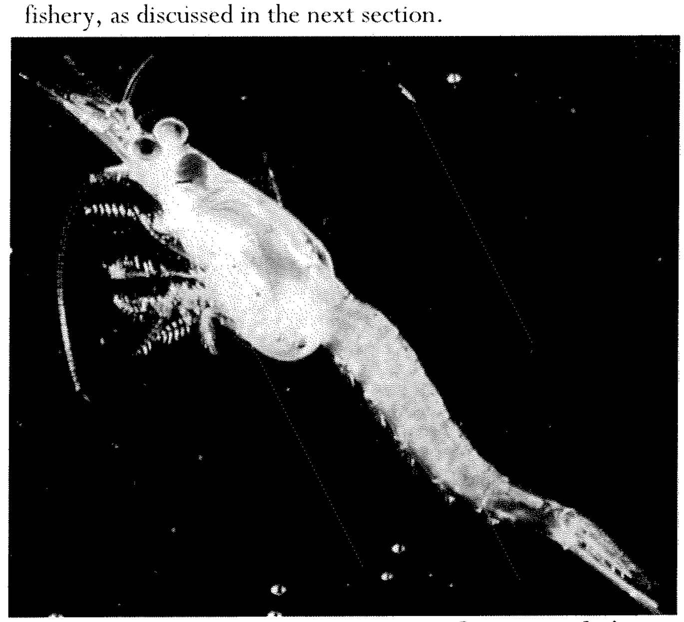
Figure11: The introduction and expansion of zebra and quagga mussels (Dreissena) (open circles) near the mouth of the Niagara River corresponded with a steep decline in numbers of the native fingernail clam (Sphaerium) (bars) from 1991-1995. (Mills et al., 2003)

Because fingernail clams can be important food sources for certain fish (for example, these clams were among the food items encountered most frequently in the diet of lake whitefish in southern Lake Michigan in the late 1990s),[95] reductions in their numbers could lead to additional foraging pressures on fish that consume them, in particular if zebra mussels are not eaten.

Another Species that May Be at Risk - Opossum Shrimp

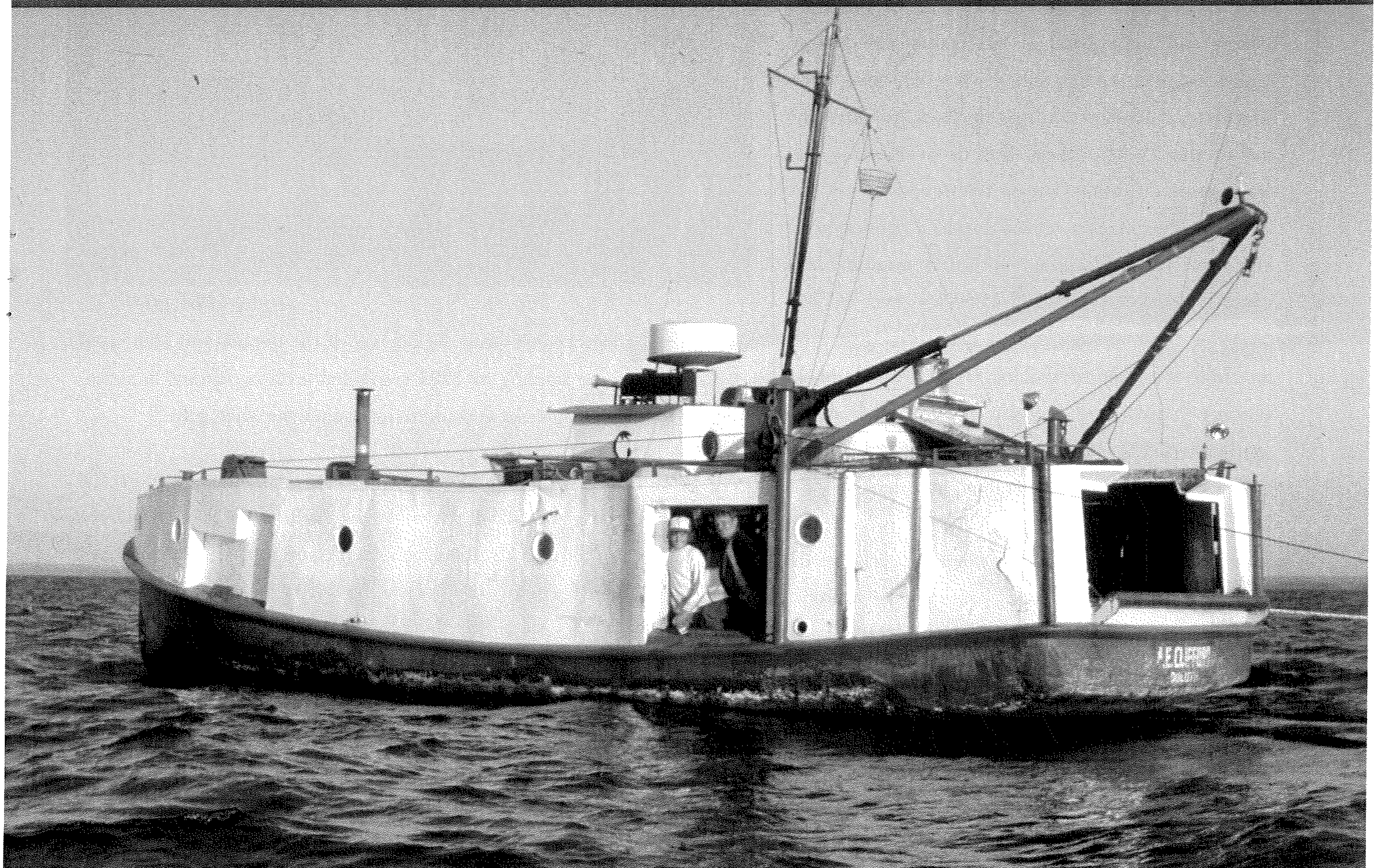
Another important component of the food web is the opossum shrimp. This organism, which can grow up to about 1.5 inches long, feeds on a variety of zooplankton, and can move up and down through the lower, cooler waters of a lake.[96] It is an important food source for a number of fish species in open lake waters, including forage fish such as deepwater sculpin, smelt, alewives, and bloaters, as well as lake whitefish.[97] Research off of Muskegon, Michigan in southern Lake Michigan found that as the percentage by weight of *Diporeia* in the diet of lake whitefish declined from 70 percent to 25 percent from 1998 to 1999-2000, the intake of opossum shrimp increased from four percent to nearly one-third of the total.[98] Although research has yet to find declines in opossum shrimp populations, increased predation by fish that would otherwise feed more on *Diporeia* could lead to substantial pressures on these shrimp populations.

The dramatic decline -- to the point of disappearance -- of these foundation species represents a sea-change in the food web and the entire Great Lakes ecosystem. Although the causes have not been conclusively proven, scientists believe that invasive species -- particularly zebra mussels -- are the likely culprits. Regardless of the causes, we already are seeing substantial damage ripple throughout the Great Lakes fishery, as discussed in the next section.



Opossum shrimp

5~ Impacts on Fish Communities and Commercial Fisheries

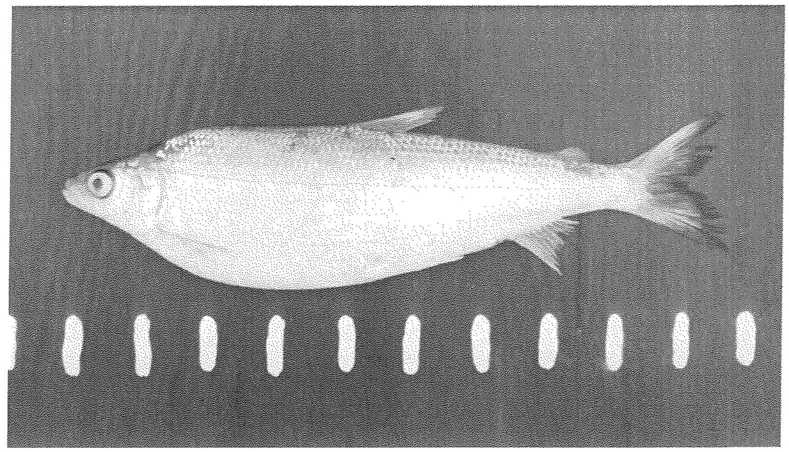


Fishermen trowling for smelt

The commercial fishing industry has adjusted to many dramatic changes in Great Lakes fish communities due to exotic species introductions – from around 60,000 metric tons annually around 1900, commercial fish harvests remained near 45,000 tons per year through most of the 20th Century.[99] In fact, recent restoration efforts have revealed positive results – for example, lake trout are again naturally reproducing in Lakes Michigan and Huron, and are apparently self-sustaining in Lake Superior; burbot populations have come back to some extent in the upper Great Lakes.[100] Restoration efforts must now address the possibility that there will be a loss of basic components in the food web; in particular, the disappearance of *Diporeia* may prove to be the most devastating result of invasive species to date, as well as one of the most challenging blows from which to recover.

The disappearance of *Diporeia* may destroy the link between the best food supply and the fish.[101] Following the zebra mussel invasion in Lake Ontario, alewives and rainbow smelt (which feed in part on *Diporeia* there), and juvenile lake trout moved to deeper water. Alewife and rainbow smelt, both fish that support trout and salmon stocks, used to obtained 40% and 11% respectively of their energy budget from *Diporeia*.[102] The shift of these species to deeper water has likely increased the importance of the opossum shrimp in their diets, although it has not necessarily led to increased growth rates in the colder water.[103] The relationship between this disruption in food levels and selected fish species is discussed below.

LAKE WHITEFISH: Lake whitefish are widely distributed in North American freshwater lakes. They are a staple of the Great Lakes commercial fishery and a mainstay of the traditional Native American diet. Great Lakes whitefish have been subject to at least two major declines, towards the end of the 19th Century, due to overfishing and drainage modification, and in the middle of the 20th Century, due in part to sea lamprey predation.[104] More recently, the average annual commercial lake whitefish harvest from 1995-1999 was over 50% of the total commercial catch in Lake Michigan each year.[105] But following the arrival of zebra mussels in 1989, the average length and weight of these fish decreased in southeastern Lake Michigan.[106] One measure of a fish's size is its condition factor, determined by calculating the ratio of its weight to its length cubed. A lighter, more emaciated fish has a lower condition factor. Figure 12 shows declines in condition factor of three age classes of lake whitefish in Lake Michigan since a population peak in 1992. While reduced growth rates in the 1990s may have been partly attributable to factors involving the density of the populations, the rapid decline starting in 1995 coincided with significant increases in zebra mussel density in northern Lake Michigan.[107]



Lake Whitefish

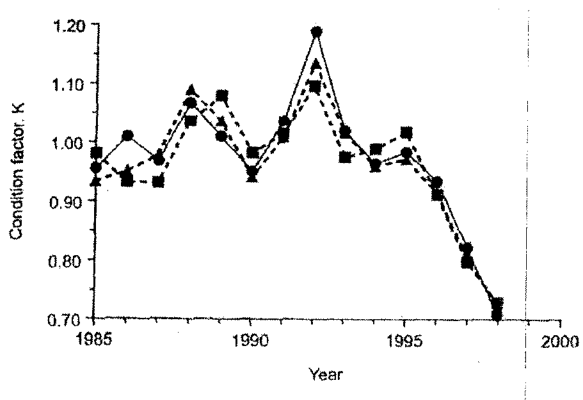


Figure 12: *Crash Diet: Following an explosion of zebra mussels in Lake Michigan during the 1990s and the near-disappearance of the water body's prized food source, Diporeia, lake whitefish experienced drops in weight in relation to their length – a measurement known as condition factor. Researchers assess the health of fish populations by tracking condition factor. Mean condition factor for age-4 (circles), 5 (triangles), and 6 (squares) lake whitefish from Lake Michigan, 1985-1998 (reproduced with permission from Madenjian et al. 2002.)*

A very similar pattern is appearing 700 miles away on the eastern end of the Great Lakes chain. Lake whitefish from Lake Ontario's Kingston Basin supported 50% of Lake Ontario's total commercial harvest of all fish species in the 1990s.[108] Since 1993, whitefish body condition, decreased juvenile and adult abundance, poor survival, and reduced production have occurred as lake whitefish shifted to feeding on mussels.[109] Research into the health of Lake Huron lake whitefish in response to decreased abundance of *Diporeia* is underway.[110]

LAKE TROUT: Lake trout are native to the Great Lakes and historically supported a significant commercial fishery in all lakes but Lake Erie. As noted previously, the combination of overfishing and sea lamprey predation led to significant declines in lake trout populations. These included a complete collapse of lake trout populations in Lakes Michigan and Huron in the 1940s, and continued declines — that had begun prior to sea lamprey invasion — in Lake Superior. By the mid 1990s, lake trout were considered commercially extinct from all of the lakes except Superior. An additional insult to lake trout in at least one lake came from toxic chemicals: a retrospective assessment indicates that exposures to dioxin-like chemicals (including dioxins, furans, and certain PCBs) alone were sufficiently high to cause complete mortality in lake trout sac fry (i.e., young fish that have not completely absorbed the food sac) in Lake Ontario through the late 1970s.[111] The combination of chemical control on sea lamprey larvae and stocking programs (and presumably declining levels of dioxin-like chemicals in Lake Ontario) have brought lake trout populations back to some degree, although only in Lake Superior are lake trout considered to be naturally reproducing at sustainable levels.[112]

In the past decade, the disappearance of *Diporeia* has imparted another blow to lake trout. Densities and body condition of lake trout dropped sharply in Lake Ontario's Kingston Basin after 1992, corresponding to the disappearance of *Diporeia* in those waters.[113] Juvenile lake trout eat *Diporeia*, and although adult lake trout do not depend directly on *Diporeia* for food, they do prefer to eat slimy sculpin in the summer months,[114] which rely on *Diporeia* for food.[115] In the past decade, densities of slimy sculpin have declined by as much as 95% in some waters of Lake Ontario.[116] In this same area, only a single specimen of *Diporeia* was collected from 18 lake bottom samples in 1997, where average densities of *Diporeia* had reached levels of 14,000 per square meter before the mussel invasion.[117] Scientists believe that drops in productivity through nutrient abatement and reduction in *Diporeia* may have negatively affected slimy sculpin populations,[118] with corresponding damage to lake trout.

In addition, zebra mussel colonies on shallow water reefs appear to inhibit successful lake trout spawning while other exotic species (carp, alewife, and round gobies) are potential predators of eggs and fry.[119] Recent research has indicated that an adult diet high in alewives has contributed to thiamine deficiency, which can also lead to mortality of lake trout fry.[120]

Lake trout

Yellow perch

YELLOW PERCH: Yellow perch have been important in the commercial fisheries in the four lower Great Lakes for decades, in particular in the past three or four decades in Lakes Huron, Erie and Ontario.[121] Declines in yellow perch in Lake Michigan in the 1970s were attributed to predation of larvae by the exotic alewives. Although populations rebounded in the 1980s, yellow perch recruitment (i.e., the increase in a fish population stock through reproduction, maturing, and migration) has been extremely poor since 1989,[122] for reasons that are still not clear.[123] Poor recruitment resulted in the lake-wide closure of commercial fisheries and reductions in bag limits for recreational anglers by the mid-1990s. In southern Lake Michigan, yellow perch survival and recruitment is closely tied to zooplankton abundance. Density of nearshore zooplankton had declined by a factor of 10 between 1988 and 1990 and remained low during 1996-1998, and may have contributed to yellow perch declines.[124] Although no firm evidence yet exists, it is possible that declines in *Diporeia* populations in southern Lake Michigan have also contributed to poor recruitment of yellow perch. Because they are also preyed upon by fish such as walleye, muskellunge, northern pike and burbot, yellow perch recruitment failures can affect a number of fisheries.

6~ Prognosis for the Great Lakes

Thirty years of pollution controls and fisheries management have driven a recovery process in the Great Lakes. However, as pointed out in the most recent State of the Great Lakes report, while a number of indicators are trending positive (e.g., meeting of phosphorus targets in all lakes but Erie, recoveries of bald eagle populations on Great Lakes shorelines), the introduction of non-native species has dramatically disrupted the Great Lakes ecosystem already, and threatens to grow worse.[125] The combination of invasive species and other threats to the ecosystem will make meeting the goals of the Great Lakes Water Quality Agreement that much more difficult. And a lack of sophisticated management tools combined with the complexity of the system will make management of the system challenging.[126]

Predicting Impacts

Predicting the impacts of new invasive species requires taking into consideration how the species will interact with the new environment as well as with other species, both native and non-native. Additionally, forces such as climate change may make determining the challenges of future Great Lakes system management even more challenging.[127] Sometimes the identification and management of new nuisance species may not occur for an extended period of time after initial exposure. Based on records of deliberate species introductions, it may take several years before the invader is detected in the system, depending on the speed of dispersal and type of organism.[128] This additional passage of time may obscure the linkage between the species and the damage it is causing, particularly since this link may not be direct or linear.[129]

Scientific predictions suggest that the Great Lakes and St. Lawrence River system will continue to receive new and potentially more damaging invasions from Eurasia.[130] As each new species becomes established, the ecosystem will respond to these new relationships. These changes will continue to challenge our innovative ability to adapt, especially in light of additional pressures on the Great Lakes ecosystem.

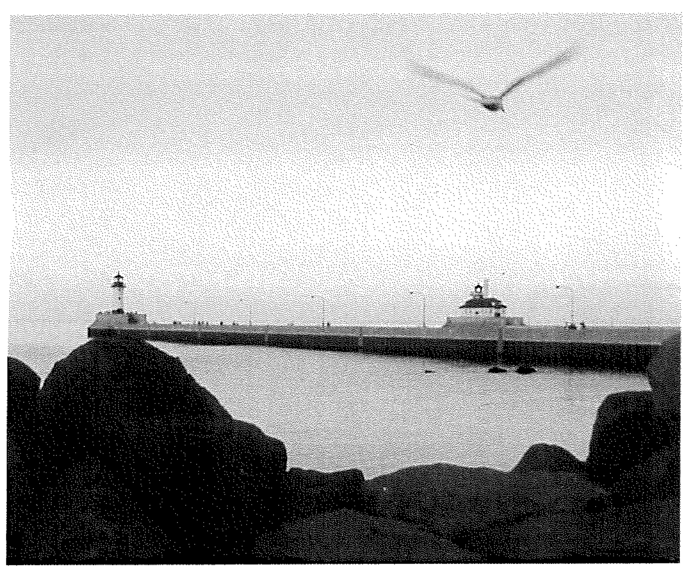
The Great Lakes Will Dramatically Change if We Don't Take Action

Unless additional action is taken quickly, the number of invasive species entering the Great Lakes will likely continue to dramatically increase. Researchers use considerations including potential donor regions with growing economies, trade patterns, attributes of species likely to facilitate invasion, and history of successful invasions in order to identify new species that could potentially invade the Great Lakes.[131] An important characteristic is examining species in regions from which successful Great Lakes species invasions have occurred. One study identified 56 fish species from the Ponto-Caspian region of Eurasia as potential invaders to the

BOX 6

Climate Change and the Great Lakes - Potential to Exacerbate Problems from Invasive Species

Climate change is being increasingly recognized as a serious problem for the Great Lakes. Computer models indicate that the climate in general could be as much as 7 degrees warmer by the end of this century. The models also indicate widely varying predictions on impacts of climate change on lake levels in the Great Lakes, ranging from as much as a 1.38 meter (4.6 ft) drop in Lakes Michigan and Huron by 2090 to a 0.35 meter (1.2 ft) increase in levels for the two lakes. The different predictions are generally due to difference in predicted precipitation levels and increases in air temperature. Other computer modeling predicts that the lakes would be warmer and more static for longer periods of the year (e.g. stratified with warmer water on top during warmer months), which could lead to reductions in nutrient cycling as well as lower penetration of oxygen to the deeper waters in the lakes. Though the potential food web repercussions of these changes are not clear, potential effects include reduced primary production (e.g., the production of algae), reduced generation times for most invertebrates, and reduced habitat for coldwater fish such as trout and salmon due to lower oxygen levels in deeper waters.[132]



Great Lakes dock

Duluth, MN

Great Lakes through the primary pathway of entry – the release of ballast water from ocean-going vessels originating in foreign ports.

Under the Non-Indigenous Aquatic Nuisance Species Prevention and Control Act of 1990, ships entering the Great Lakes from the oceans are required to either carry no ballast water when entering the Great Lakes ("No Ballast On Board" vessels, or NOBOBs), or to exchange their ballast water at sea, in theory dumping any invaders into the ocean before they reach the Great Lakes.

Policy Actions

The invasion of the sea lamprey and ensuing crash of several commercial fish species led to the establishment of one of the most successful invasive species control programs – the sea lamprey control program – which has reduced lamprey populations by 90%, according to the Great Lakes Fisheries Commission, which manages the program in conjunction with the U.S. Fish and Wildlife Service, Army Corps of Engineers, and Fisheries and Oceans Canada. The program costs between $10 million and $15 million annually, and, its success notwithstanding, has underscored the challenge of mitigating the effects of invasive species in an environment in which they have already established themselves.

Great Lakes states have also enacted statutes to prevent the introduction and spread of invasive species. Through a patchwork of legislative initiatives, states have attempted to monitor and regulate the importation, transportation, stocking, possession, sale and release of non-native species such as fish and bait.

Recent efforts to combat invasive species have focused on preventing new non-native organisms from entering the

But after extensive study, scientists have concluded that NOBOBs and ballast water exchange are not effective at stopping the introduction of new invasive species into the Great Lakes. Salt water may kill freshwater organisms. However, brackish water species such as crustaceans and algae may survive the exchange treatment.[140] Furthermore, despite their name, NOBOBs do contain residual ballast water and sludge that the pumps cannot remove. NOBOB vessels entering the Great Lakes typically carry between one to two hundred metric tons of unpumpable slop and sediment in the bottom of their tanks.[141] As the ships unload their cargo and take in Great Lakes ballast, the residual ballast mixes with the new water, resuspending non-native organisms and then releasing them when they take on and discharge ballast during their voyage through the lakes. Ballast water exchange at sea fares no better, for the same reason. Such exchanges cannot remove all organisms from ships' ballasts; so even after an exchange at sea, ships entering the Great Lakes can carry harmful organisms that they discharge as they travel through the lakes. And of course, ballast water exchange cannot address invasive species that attach to the hulls of ships.

Far more protection is needed. There are a number of immediate and important actions the federal government and regional leaders should take to address invasive species to prevent further damage to the Great Lakes food web and fishery. These include:

***National Legislation*:** Congress is considering comprehensive national legislation – the National Aquatic Invasive Species Act (S.525), or NAISA – that would regulate the most common routes of nuisance species introduction in the United States, including the nation's first implementation of standards for ballast water discharges. NAISA's enactment is a top priority; but it is also part of a long-term solution. The Great Lakes need even more rapid action than the bill would provide.

***Voluntary action*:** The shipping industry has recognized its role in the introduction of aquatic invasive species. Recently, the International Maritime Organization (IMO) issued international ballast water standards for vessels. The IMO standards are weak and do not go far enough in protecting the Great Lakes. Those standards have also not been ratified by the necessary 30 nations representing 35 percent of world shipping tonnage. Nevertheless, the shipping industry does not have to wait for government action; it can take measures now to prevent the introduction of new harmful species. Over the past several years, ballast water treatment technologies have been tested to reduce the probability of invasive species introductions. Great Lakes carriers, ports and shippers can commit to developing and installing innovative and effective treatment technologies, rather than waiting for the public outcry and legal liability that could accompany a new infestation by a harmful invasive species.

***Great Lakes Restoration*:** Congress also is considering pending legislation that would provide $4 billion-$6 billion to restore the Great Lakes. These funds would be spent in a number of areas, including invasive species control, clean up of contaminated sediments, prevention of additional water pollution, and habitat restoration. The funds may also be spent on research projects (including the research discussed below) that are critical to understanding and addressing the massive disruption of the Great Lakes food web.

RESEARCH ACTIONS

Scientists have made strides in determining the extent of the disruption of the Great Lakes food web, the causes of that disruption, and its consequences. However, there are critical knowledge gaps that must be filled before we know how to restore the food web or at least minimize the damage done to it. More research is urgently needed to determine:

- The scope and severity of changes to the food web throughout the Great Lakes.
- The causes of the changes to the food web, including a better understanding of multiple interacting factors where identified.
- The impacts that food web disruptions have already had on other aquatic species, and the likely future impacts given current trends. Current impacts need to be measured directly to the greatest extent possible. Additional data gathering and computer modeling on food web interactions is necessary to identify potential

Great Lakes marina

Box 7

Getting a Handle on Invasive Species: The Challenges of a Coordinated, Effective Response

Jurisdictional management of resources in the Great Lakes drainage basin is complex – involving the federal governments of the United States and Canada, bureaucracies from two provinces and eight states, and Native American tribes.[142] Further, policy and management guidance is provided by the International Joint Commission and the Great Lakes Fisheries Commission.

U.S. government agencies at all levels have adopted programs to restore and protect the environmental quality in the Great Lakes region. In a 2003 report, the U.S. General Accounting Office (GAO), the investigative arm of Congress, found that within seven federal agencies there were 33 programs that were specifically designed to address environmental conditions in the Great Lakes through activities such as research, cleanup, or pollution prevention. The federal government spent $387 million in fiscal years 1992 through 2001 on these programs. During this same time, the Army Corps of Engineers spent $358 million on projects in the Great Lakes basin, as directed by Congress. And, according to the GAO, officials from seven states reported 17 Great Lakes specific programs that expended about $956 million in 1992 through 2001. In its assessment of these Great Lakes restoration efforts, the U.S. General Accounting Office found that there is no single agency in charge of the Great Lakes to coordinate various programs, resulting in a menu of Great Lakes programs that are often fragmented, uncoordinated and underfunded.

The GAO found that similar problems plagued national efforts to combat invasive species. In 1999 President Clinton signed an executive order to ramp up the government's response to invasive species and curtail the damage caused by non-native organisms to the environment, economy and health of the country. The executive order established the National Invasive Species Council (NISC) to provide leadership on invasive species initiatives – including responsibilities to ensure federal initiatives are coordinated and effective.

As part of this charge, the NISC crafted a federal management plan, issued in 2001, to coordinate the national effort to control invasive species among the 20 or so federal agencies that currently have jurisdiction in that area. In a study released in June 2003, the GAO found that the federal management plan for addressing invasive species included actions that would lead to the control of, monitoring and response to invasive species – though it lacked clear outcomes and measures of success. Further, the GAO found that implementation of the plan was slow due in part to lack of funding and staff to carry out he work. The 2003 study also identified other obstacles in combating invasive species, including gaps in existing legislation and lack of an effective ballast water standard. The report detailed major concerns by state officials, including a lack of federal funding, public education and outreach, and cost-effective management programs.[143]

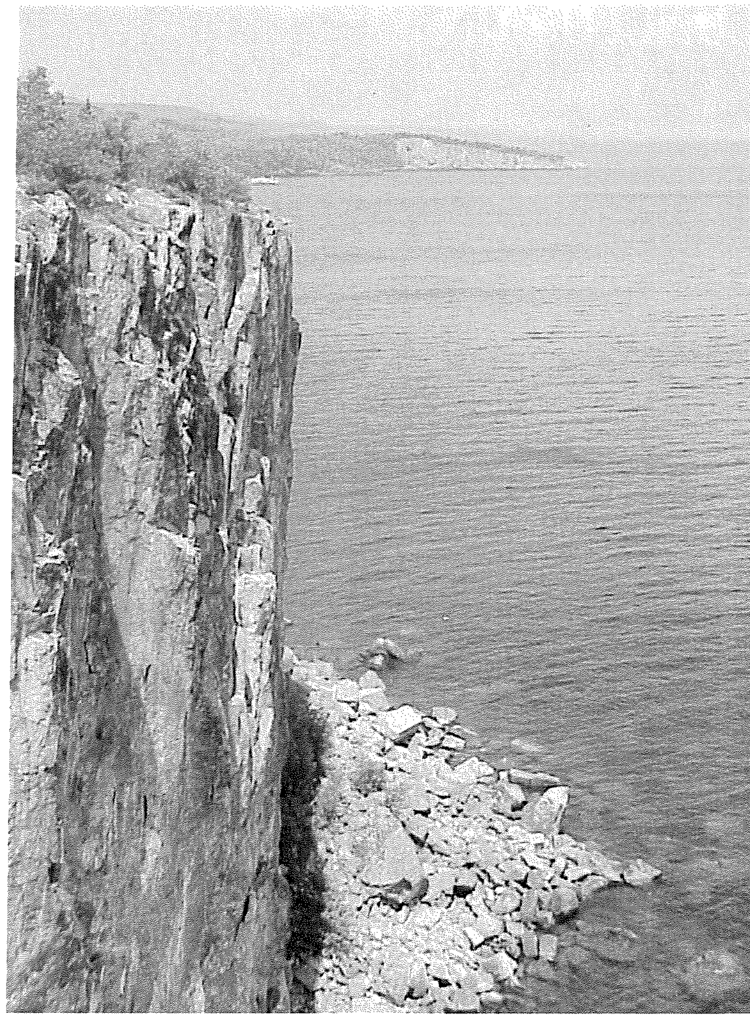
future impacts of food web disruptions in the Great Lakes.

- The design of new management tools to address the damage to the food web and its ripple effects throughout the lakes. Existing tools are inadequate.

In addition, since all potential invaders may not be prevented from entering the Great Lakes, research should be aimed at prioritizing threats, through means such as:

- Identifying potential donor regions and dispersal pathways of future invaders;
- Selecting potential invaders using biological criteria;
- Using invasion history as a predictive criterion;[144]
- Examining instances of failed invasions to identify limiting factors.[145]

While researchers have been addressing various aspects of these issues, it is clear that current research capacity and activity must increase to address these potentially serious changes to food webs. Significant additional funding is urgently needed, and state and federal fisheries agencies need to establish this research area as a top priority within their budgets and staffs.



Public Education

State funding will not be enough. According to the U.S. General Accounting Office, federal funds – especially new federal funding through Great Lakes restoration financing legislation currently pending in Congress are essential.

Policymakers and the public for years have heard about toxic pollution, water diversions and habitat destruction in the Great Lakes, and the general level of public understanding of these issues is relatively high. In the past few years, invasive species also have gained considerable notoriety. But few outside the Great Lakes scientific community understand the radical and harmful changes these problems have caused for the Great Lakes food web, fishery, and overall ecosystem. That limited awareness must change. The Great Lakes are in the midst of what may be an ecological meltdown – and the public and many policymakers do not yet know. The Great Lakes will not receive the attention they need in the time frame they need it unless public awareness of the problem changes dramatically.

A great number of mechanisms are available to bring about this change. A few include:

- Organized hearings, in Washington D.C. and in the region, to explore and highlight the problem.
- The convening of panels of knowledgeable scientists by conservation and business associations at regional and national meetings.
- State legislative and agency hearings.
- Priority-setting by regional organizations, such as the International Joint Commission, the Council of Great Lakes Governors, and the Great Lakes Cities Initiative.
- Continued education and outreach through state Sea Grant programs, and increased efforts by state extension programs.

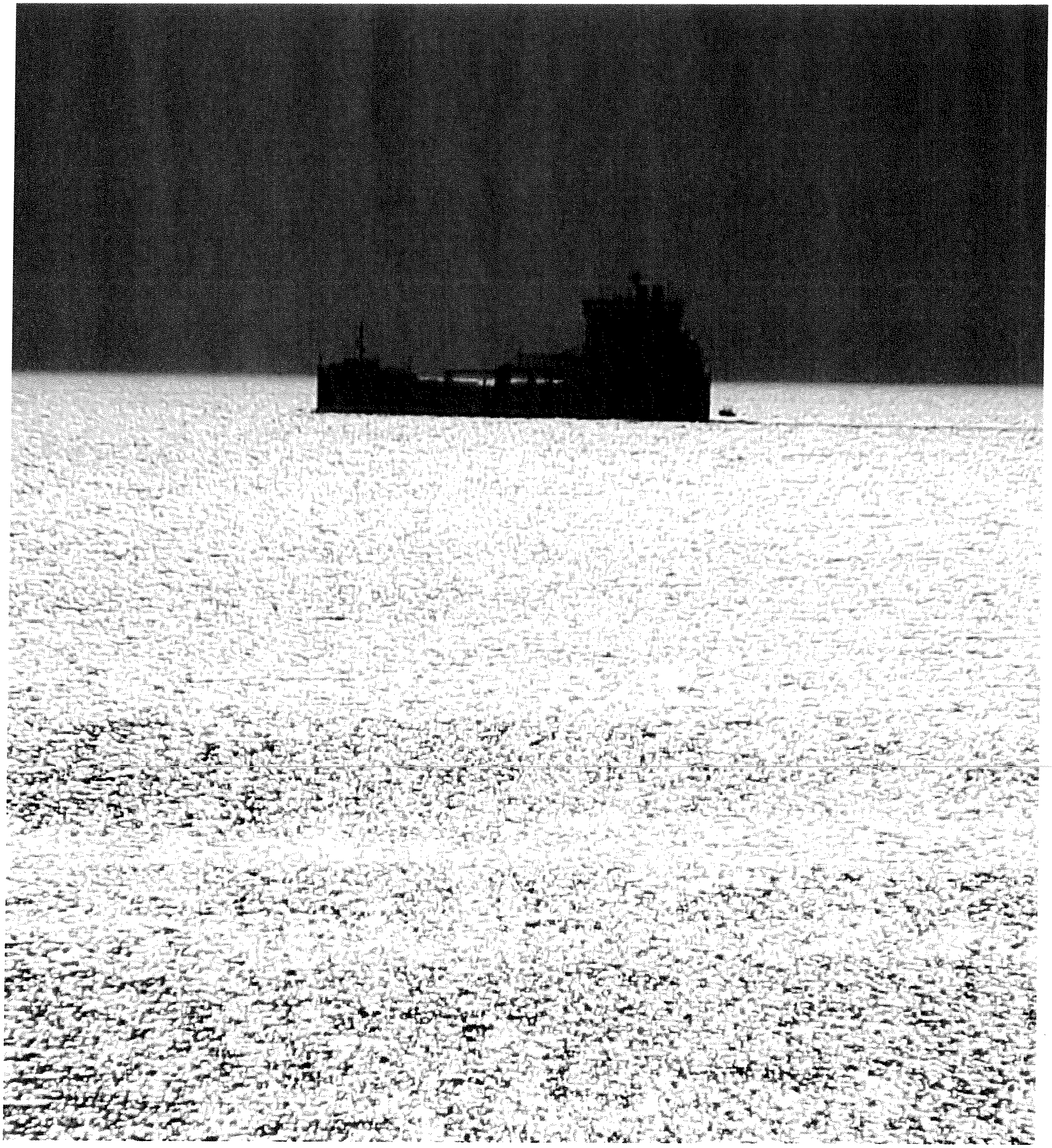
Conclusion

The Great Lakes right now are experiencing perhaps the most fundamental – and potentially devastating – changes in their recorded history. The Great Lakes food web is undergoing massive disruptions, primarily from the invasion of non-native aquatic species. We see the obvious effects of alewives washing up dead on the beaches, sea lamprey sucking the life out of lake trout, and zebra mussels clogging water intake pipes. But as damaging as these are, the research presented in this report indicates that they only scratch the surface of what's ailing the lakes.

The entire foundation of the Great Lakes food web is declining precipitously. The largest component of the base of the food web – *Diporeia*, a tiny shrimp-like organism – has nearly disappeared from large stretches of the lake bottoms. Other key components – fingernail clams and opossum shrimp – are beginning to experience similar declines. Although there is no conclusive evidence, most scientists believe that an invasive species, the zebra mussel, is the likely the culprit. And they worry that invasions by a similar species, the quagga mussel, will expand the damage to the remaining food web foundation, attacking deeper-water food sources.

The damage by invasive species is perpetual. Unlike pollution in the lakes, which can improve once new inputs are stopped, invasive species continue to reproduce and thrive even if no new species are introduced. The problem species we see now will continue to get worse without action; and new invaders (an average of one every eight months) will continue to be introduced.

The lakes need action now. They need research to better understand the disruptions to the food web, the consequences to key species, and the best methods and places of intervention. They need federal and state legislation and voluntary action to stop the introduction of new invasive species. They need new management tools to address the invaders that are already in the lakes. And they need funding to accomplish these tasks – to restore the Great Lakes. Their future, and ours, are in the balance.



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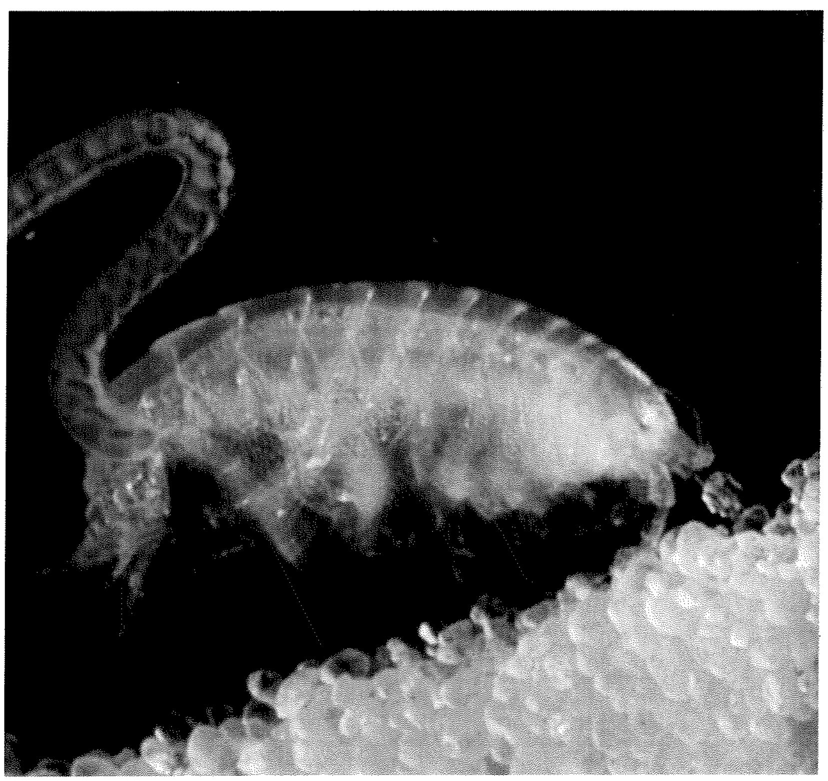

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